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Reinke et al.

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(54) **ANTI-TACHYARRHYTHMIA SHOCK DETECTION**

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A61N 1/362	(2006.01)
A61N 1/37	(2006.01)

(52) **U.S. Cl.**
CPC ***A61N 1/3937*** (2013.01); ***A61N 1/3621*** (2013.01); ***A61N 1/37*** (2013.01)

(58) **Field of Classification Search**
CPC A61N 1/36135–1/36142; A61N 1/3925; A61N 1/3956; A61N 1/36153; A61N 1/3621; A61N 1/3937; A61N 1/37; A61N 1/3962
See application file for complete search history.

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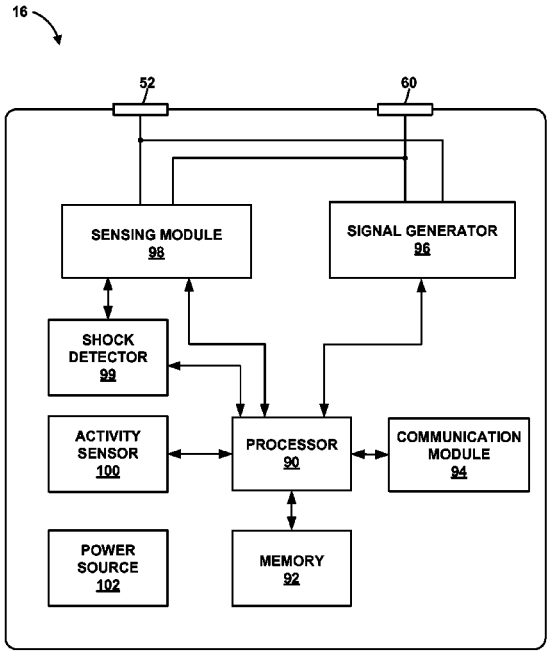
(74) *Attorney, Agent, or Firm* — Michael J. Ostrom

(57) **ABSTRACT**

An implantable pacemaker detects delivery of an anti-tachyarrhythmia shock by another device. The implantable pacemaker delivers cardiac stimulation therapy within a patient. The implantable pacemaker senses, via the electrode pair, an electrical signal. The implantable pacemaker detects the anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the electrode pair within the patient. The implantable pacemaker alters the cardiac stimulation therapy based on the detected anti-tachyarrhythmia shock.

20 Claims, 13 Drawing Sheets



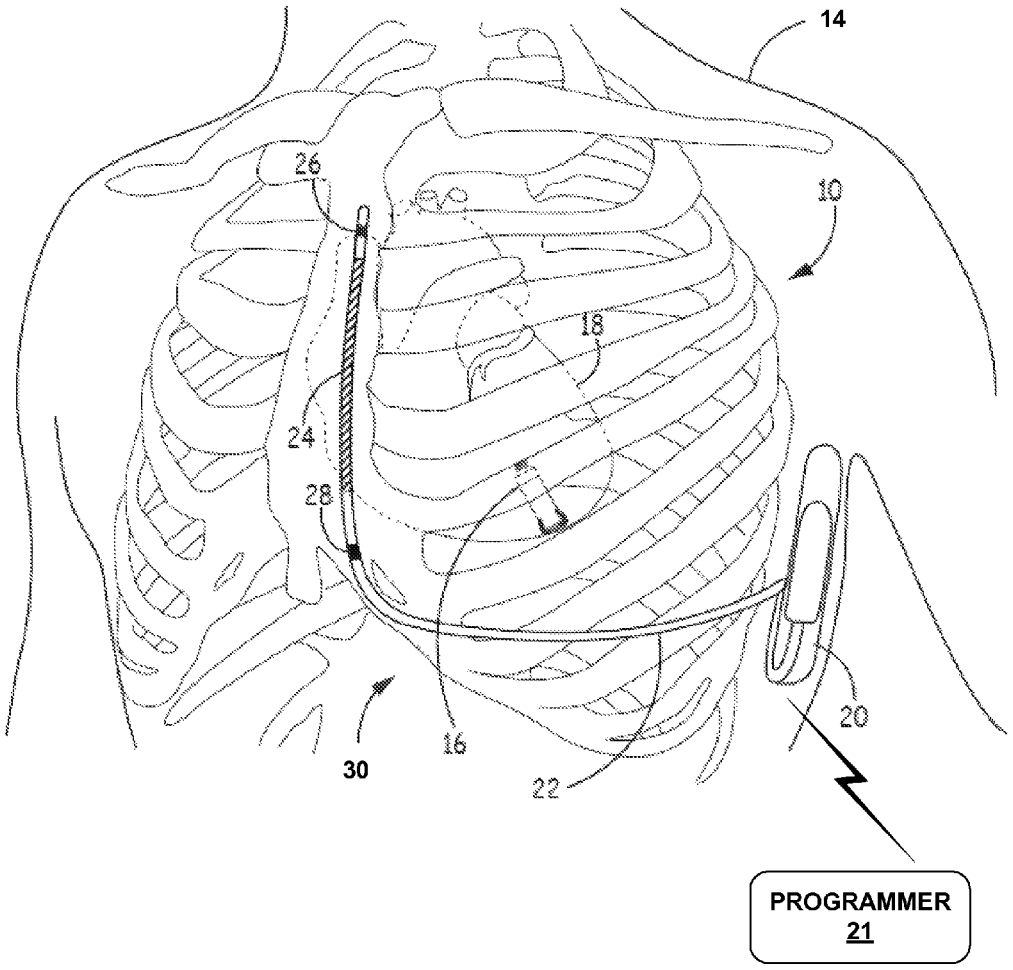


FIG. 1

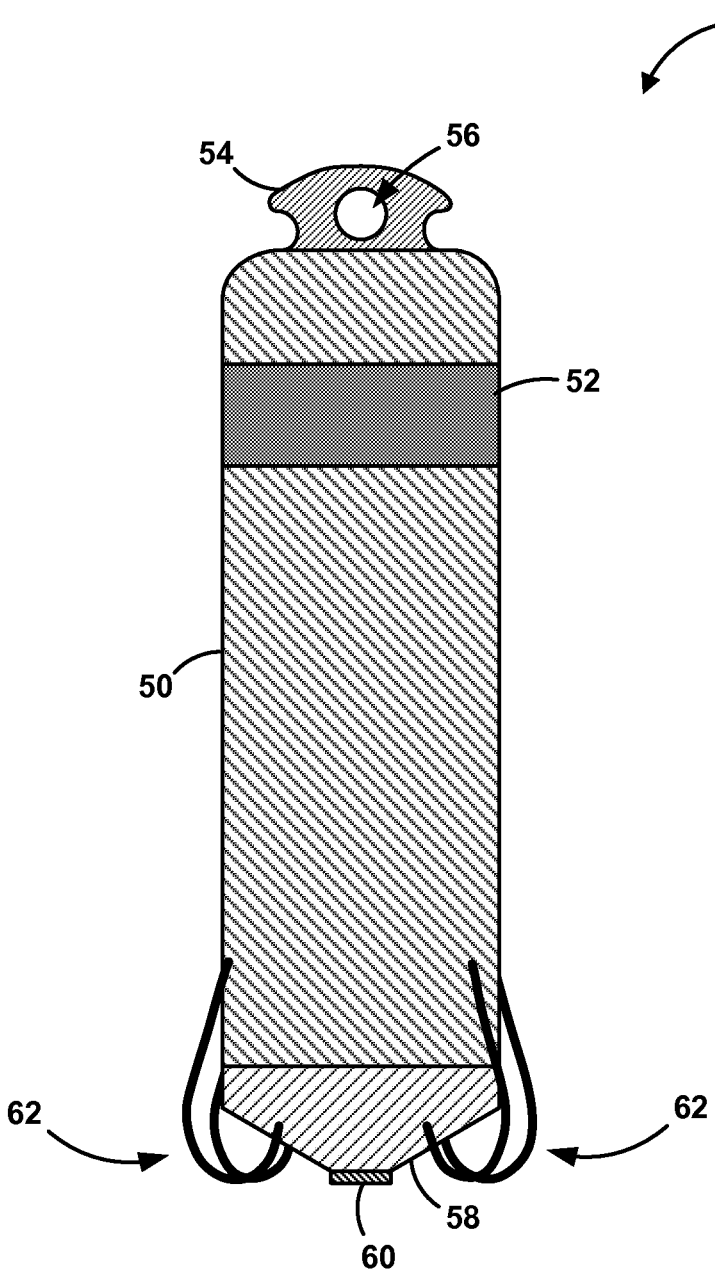


FIG. 2

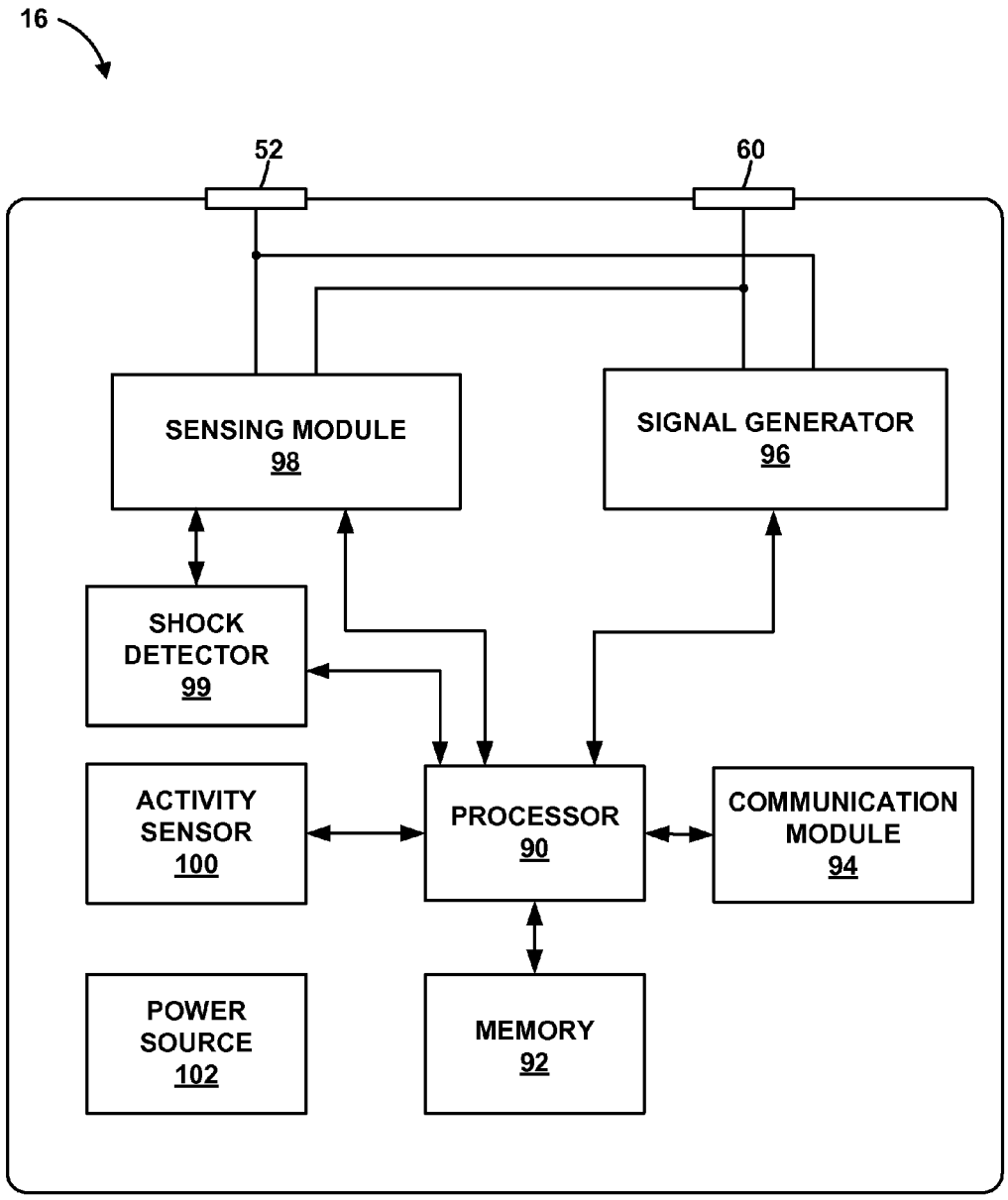

16
52
60
SENSING MODULE
98
SIGNAL GENERATOR
96
SHOCK
DETECTOR
99
ACTIVITY
SENSOR
100
PROCESSOR
90
COMMUNICATION
MODULE
94
POWER
SOURCE
102
MEMORY
92

FIG. 3

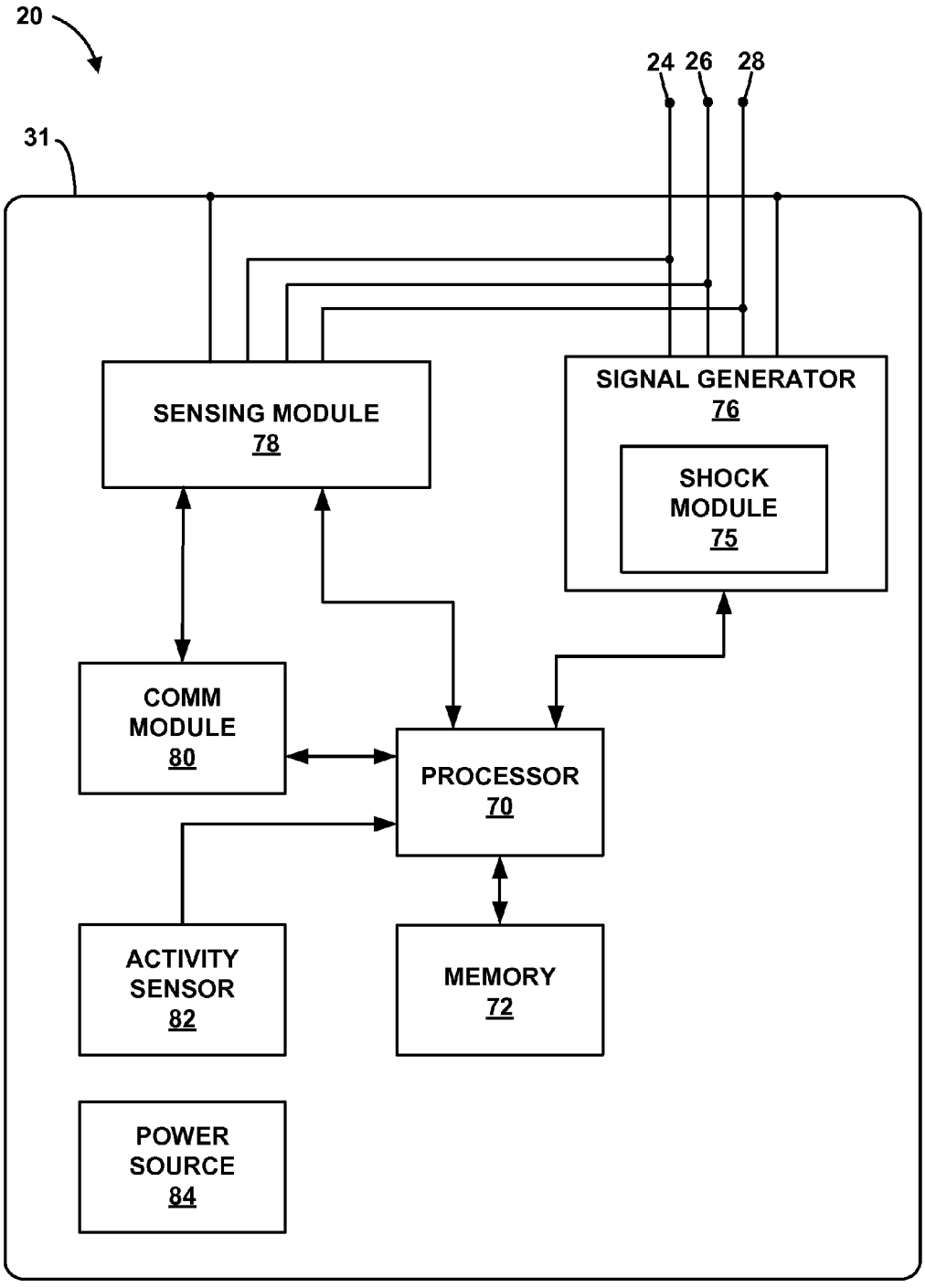

20
24
26
28
31
SENSING MODULE
78
SIGNAL GENERATOR
76
SHOCK
MODULE
75
COMM
MODULE
80
PROCESSOR
70
ACTIVITY
SENSOR
82
MEMORY
72
POWER
SOURCE
84

FIG. 4

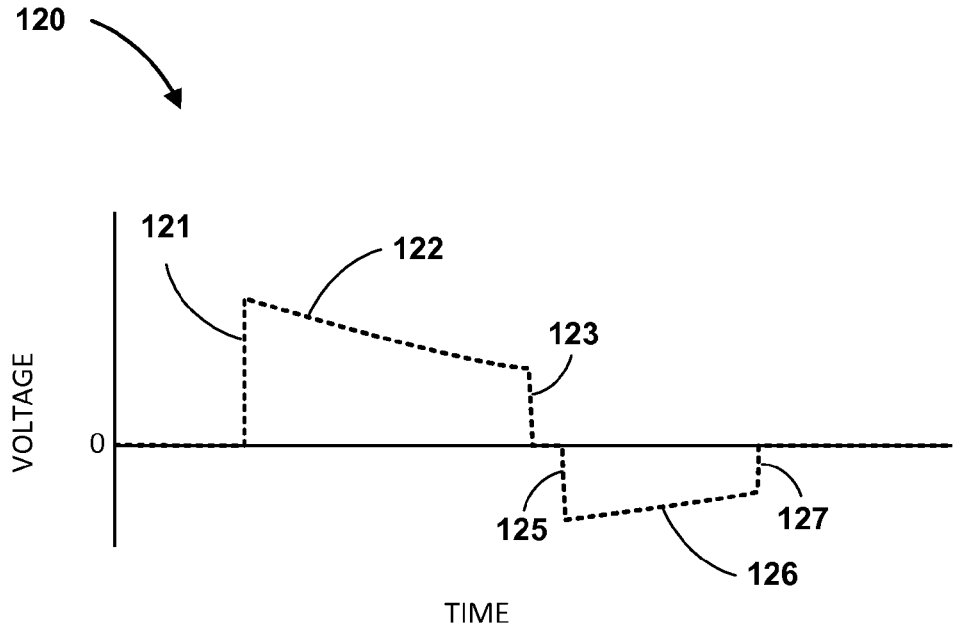

120
121
122
123
VOLTAGE
0
125
127
126
TIME

FIG. 5A

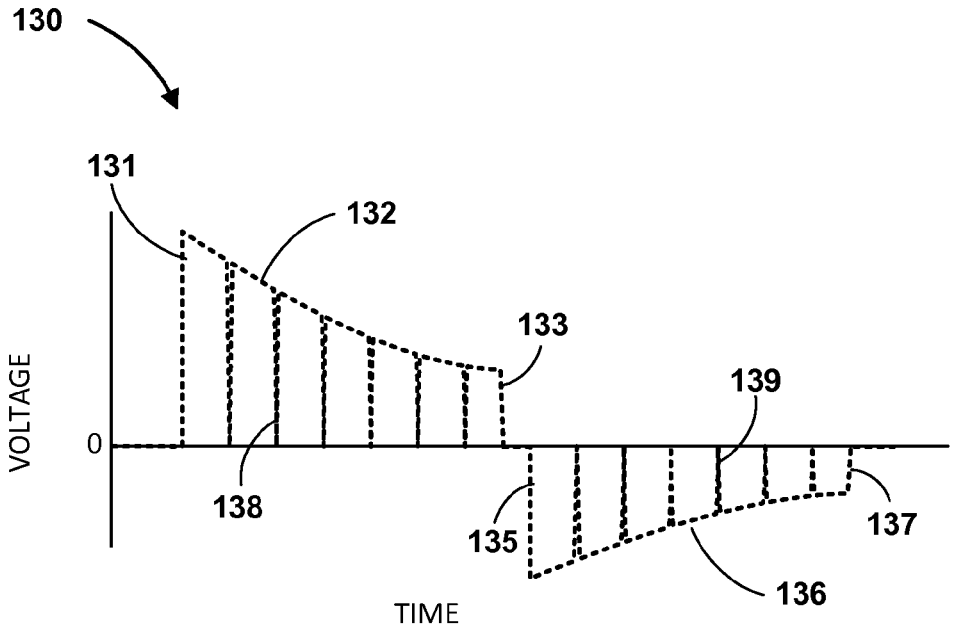

130
131
132
133
139
VOLTAGE
0
138
135
137
136
TIME

FIG. 5B

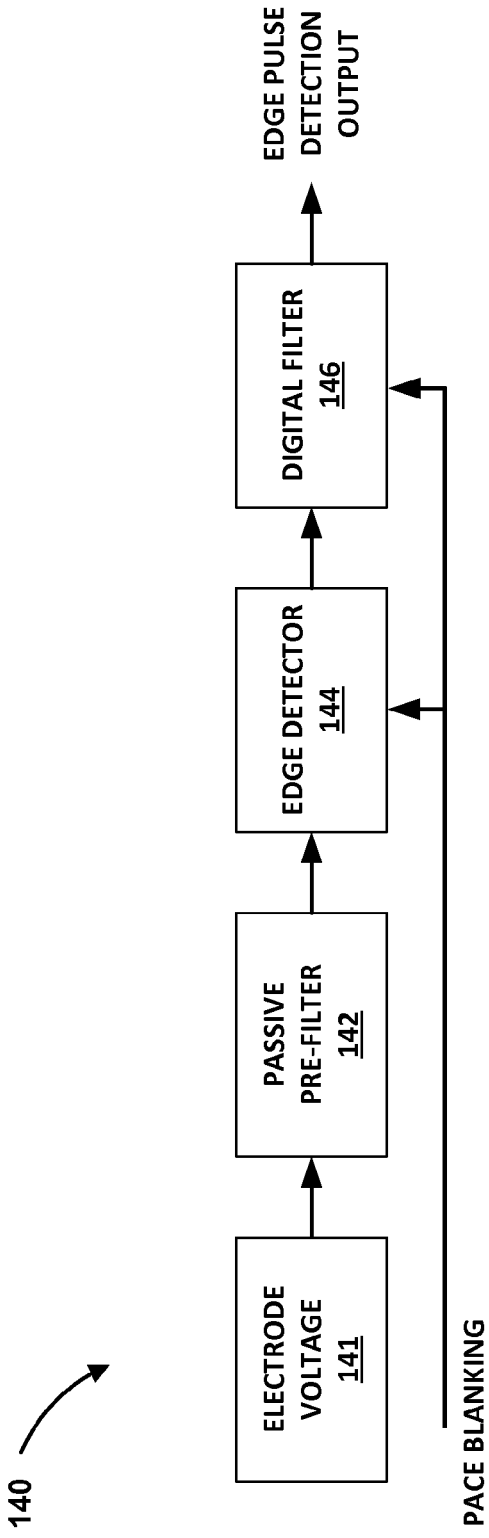

140
ELECTRODE VOLTAGE 141
PASSIVE PRE-FILTER 142
EDGE DETECTOR 144
DIGITAL FILTER 146
EDGE PULSE DETECTION OUTPUT
PACE BLANKING

FIG. 6A

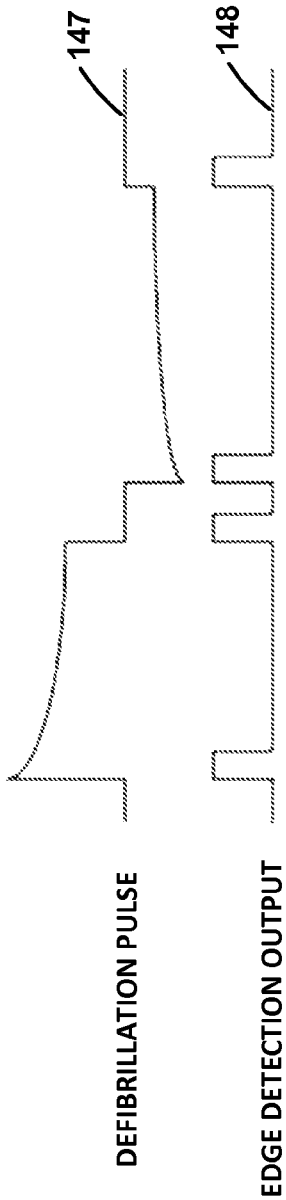

147
148
DEFIBRILLATION PULSE
EDGE DETECTION OUTPUT

FIG. 6B

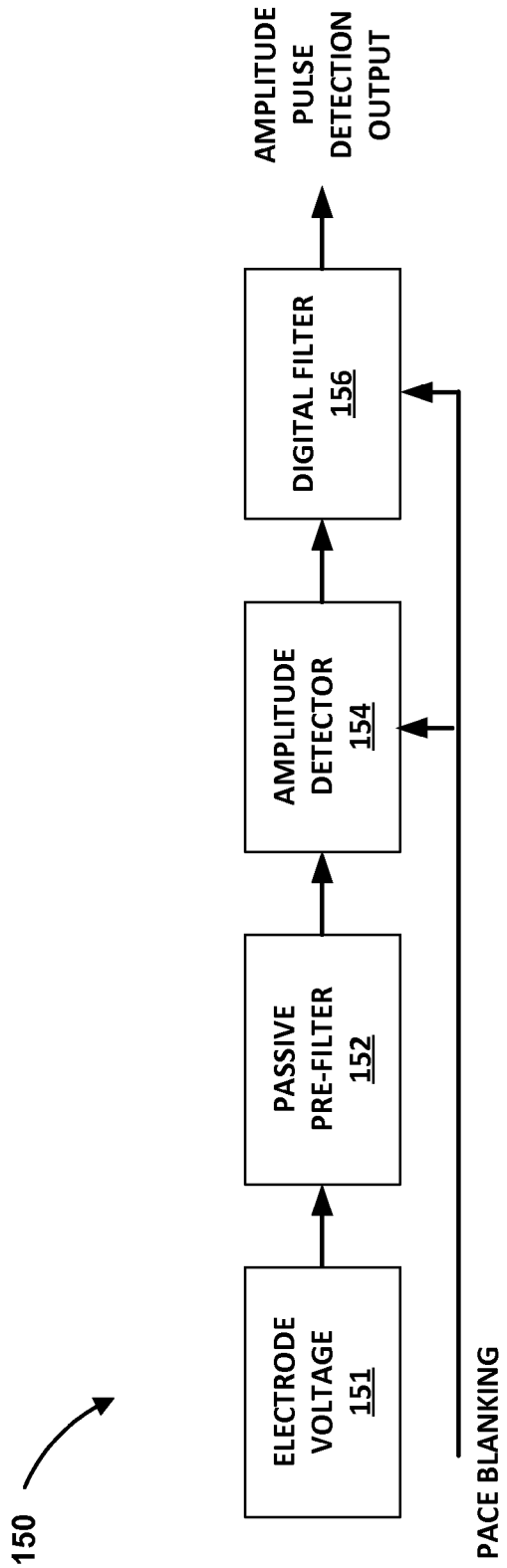

150
ELECTRODE VOLTAGE 151
PASSIVE PRE-FILTER 152
AMPLITUDE DETECTOR 154
DIGITAL FILTER 156
AMPLITUDE PULSE DETECTION OUTPUT
PACE BLANKING

FIG. 7A

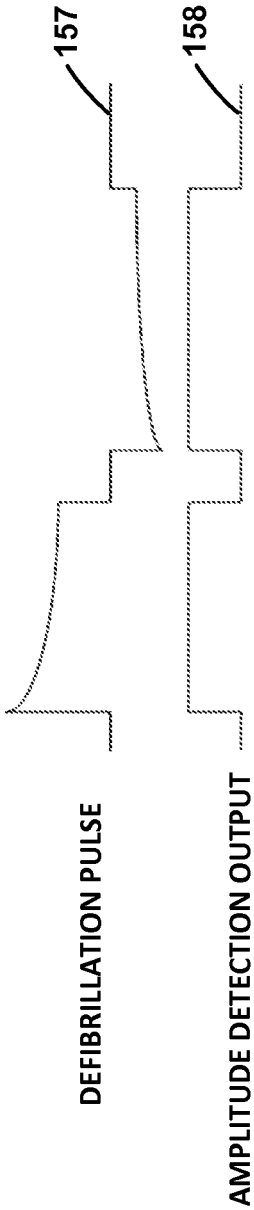

157
158
DEFIBRILLATION PULSE
AMPLITUDE DETECTION OUTPUT

FIG. 7B

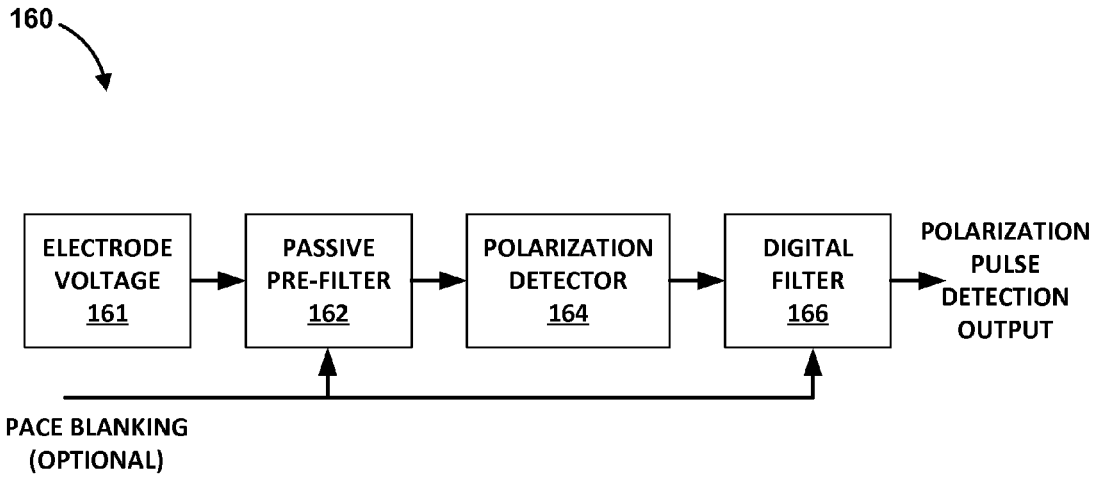

160
ELECTRODE VOLTAGE 161
PASSIVE PRE-FILTER 162
POLARIZATION DETECTOR 164
DIGITAL FILTER 166
POLARIZATION PULSE DETECTION OUTPUT
PACE BLANKING (OPTIONAL)

FIG. 8

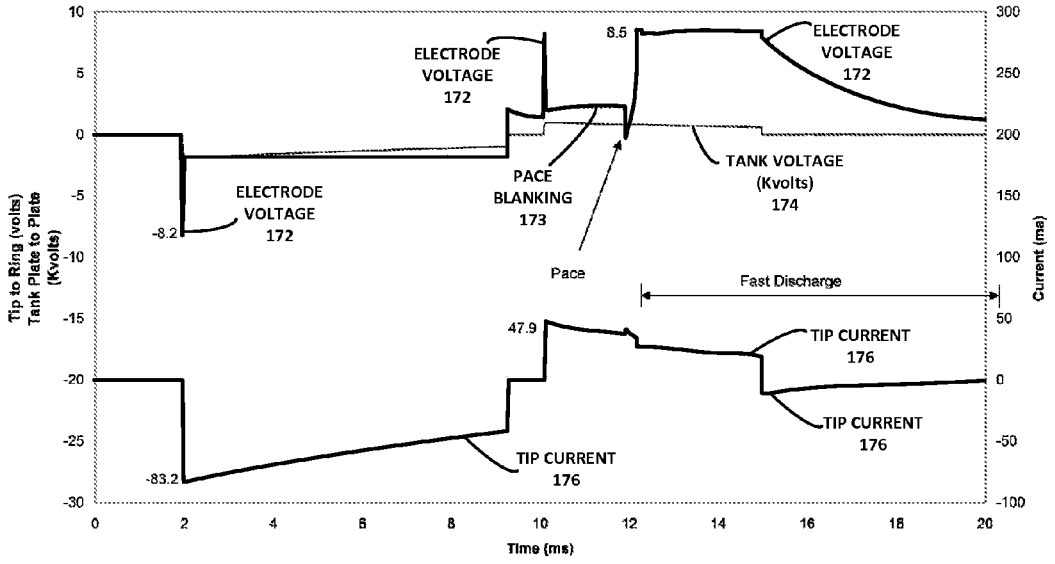

ELECTRODE VOLTAGE 172
8.5
ELECTRODE VOLTAGE 172
ELECTRODE VOLTAGE 172
-8.2
PACE BLANKING 173
TANK VOLTAGE (Kvolts) 174
Pace
Fast Discharge
47.9
TIP CURRENT 176
TIP CURRENT 176
TIP CURRENT 176
-83.2
Tip to Ring (volts) Tank Plate to Plate (Kvolts)
Current (ma)
Time (ms)

FIG. 9A

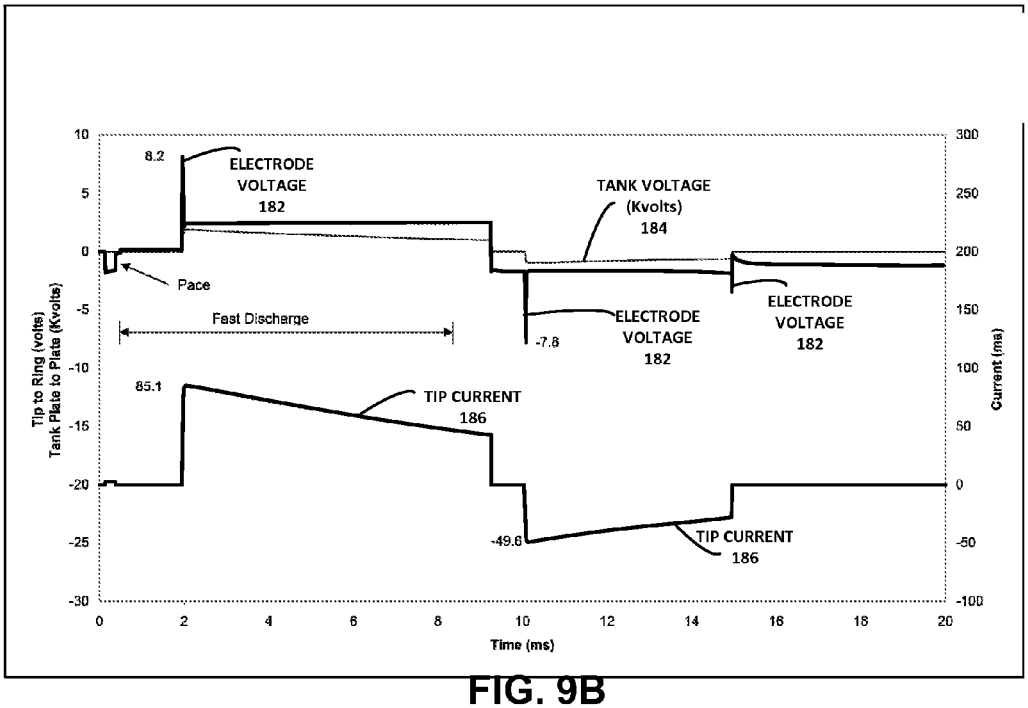

8.2
ELECTRODE VOLTAGE 182
TANK VOLTAGE (Kvolts) 184
Pace
Fast Discharge
-7.8
ELECTRODE VOLTAGE 182
ELECTRODE VOLTAGE 182
85.1
TIP CURRENT 186
-49.6
TIP CURRENT 186
Tip to Ring (volts) Tank Plate to Plate (Kvolts)
Current (ma)
Time (ms)

FIG. 9B

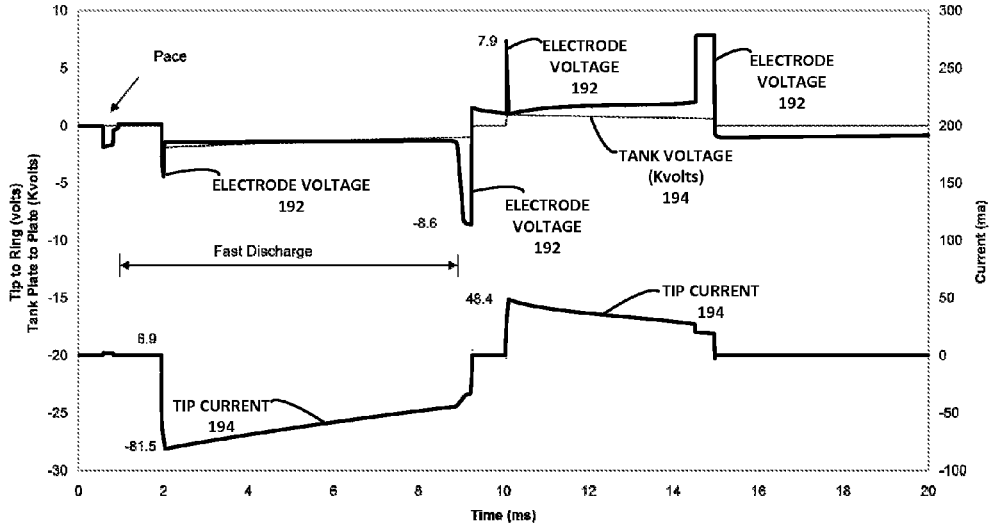

Pace
7.9
ELECTRODE VOLTAGE 192
ELECTRODE VOLTAGE 192
TANK VOLTAGE (Kvolts) 194
ELECTRODE VOLTAGE 192
-8.6
ELECTRODE VOLTAGE 192
Fast Discharge
48.4
TIP CURRENT 194
8.9
TIP CURRENT 194
-81.5
Tip to Ring (volts) Tank Plate to Plate (Kvolts)
Current (ma)
Time (ms)

FIG. 9C

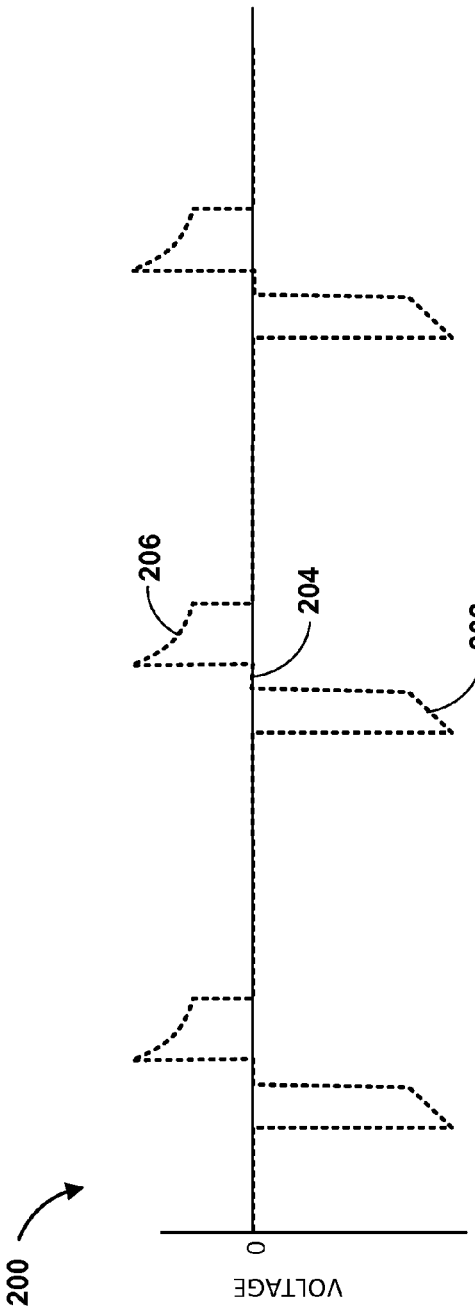


FIG. 10

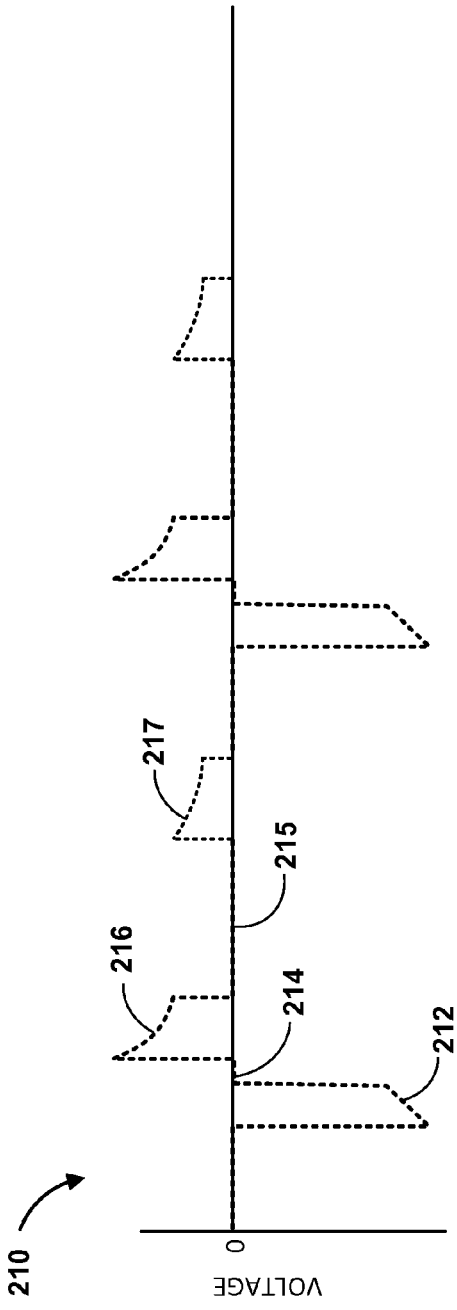


FIG. 11

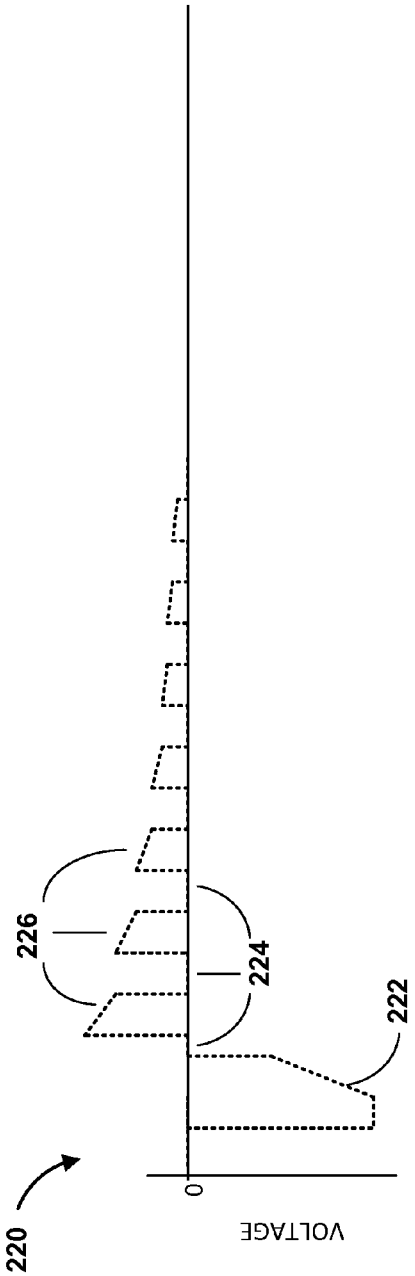


FIG. 12

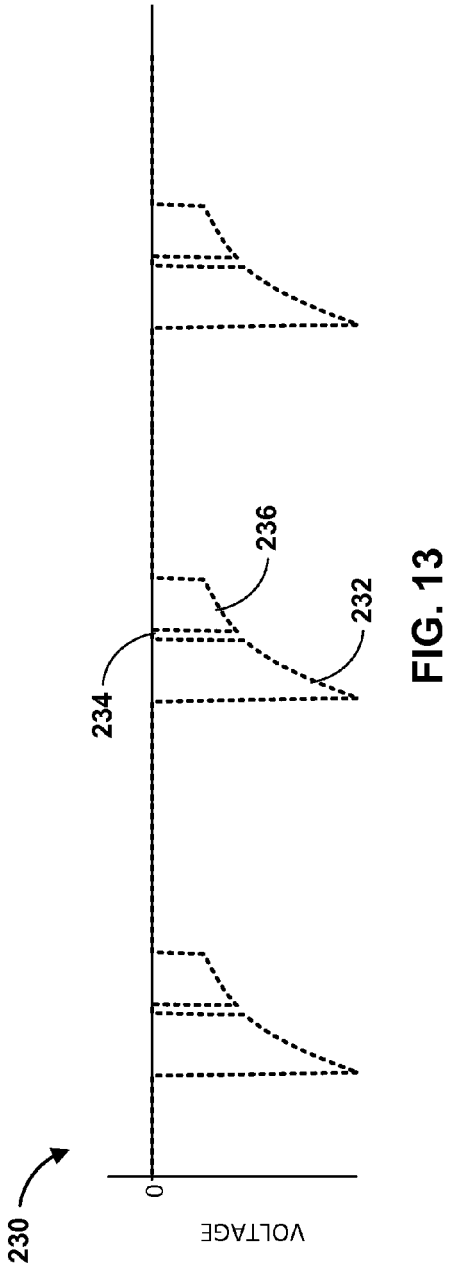


FIG. 13

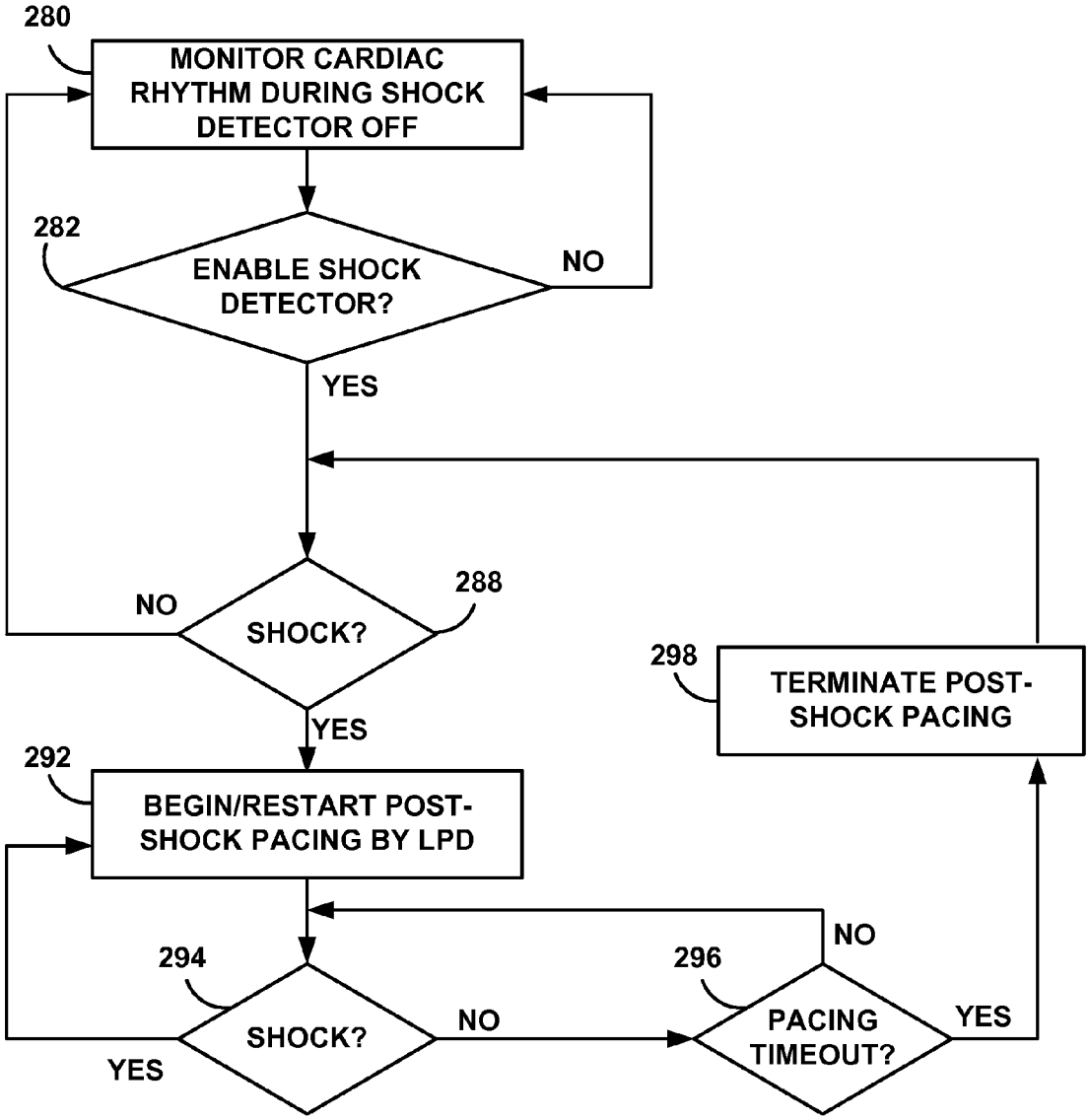

280
MONITOR CARDIAC RHYTHM DURING SHOCK DETECTOR OFF
282
ENABLE SHOCK DETECTOR?
NO
YES
288
SHOCK?
NO
YES
298
TERMINATE POST-SHOCK PACING
292
BEGIN/RESTART POST-SHOCK PACING BY LPD
294
SHOCK?
NO
YES
296
PACING TIMEOUT?
NO
YES

FIG. 14

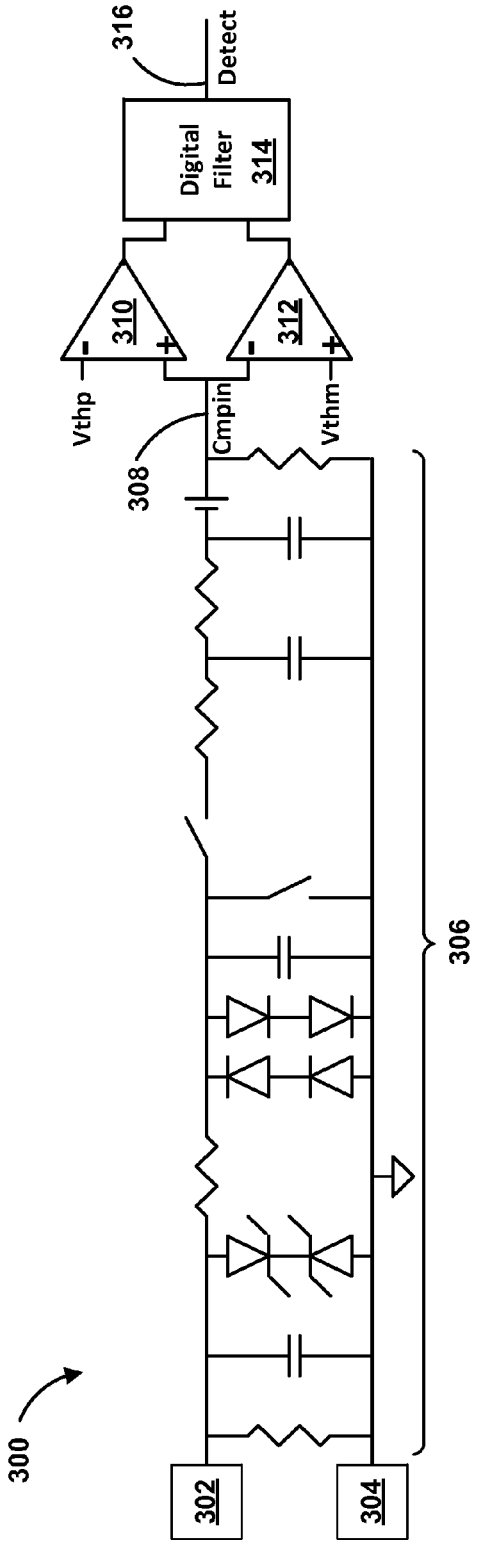


FIG. 15A

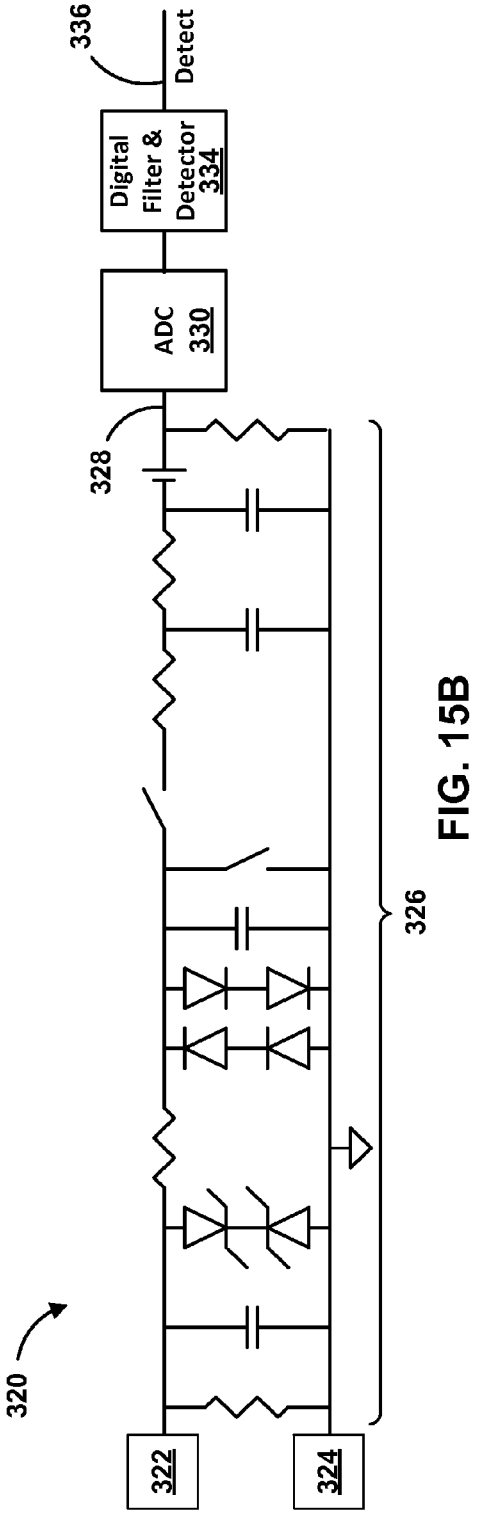


FIG. 15B

ANTI-TACHYARRHYTHMIA SHOCK DETECTION

TECHNICAL FIELD

The invention relates to medical devices, and, more particularly, to implantable medical devices configured to detect and treat cardiac arrhythmias.

BACKGROUND

Implantable cardioverter defibrillators (ICDs) and implantable artificial pacemakers may provide cardiac pacing therapy to a patient's heart when the natural pacemaker and/or conduction system of the heart fails to provide synchronized atrial and ventricular contractions at rates and intervals sufficient to sustain healthy patient function. Such antibradycardial pacing may provide relief from symptoms, or even life support, for a patient. Cardiac pacing may also provide electrical overdrive stimulation, e.g., anti-tachyarrhythmia pacing (ATP) therapy, to suppress or convert tachyarrhythmias, again supplying relief from symptoms and preventing or terminating arrhythmias that could lead to sudden cardiac death.

Cardiac pacing by conventional pacemakers and/or ICDs is usually provided by a pulse generator implanted subcutaneously or sub-muscularly in or near a pectoral region of a patient. The generator typically connects to the proximal end of one or more implanted leads, the distal end of which contains one or more electrodes for positioning adjacent to the inside or outside wall of a cardiac chamber. Each of the leads may be secured near or against the cardiac tissue to provide sufficient transmission of electrical energy to the cardiac tissue in order to capture the heart.

ICDs may also be used to deliver high-energy cardioversion or defibrillation pulses to a patient's heart when atrial or ventricular fibrillation is detected. Cardioversion shocks are typically delivered in synchrony with a detected R-wave when fibrillation detection criteria are met. Defibrillation pulses are typically delivered when fibrillation criteria are met, and the R-wave cannot be discerned from signals sensed by the ICD.

Currently, ICDs use endocardial or epicardial leads which extend from the ICD housing through the venous system into the heart. Electrodes positioned in or adjacent to the heart by the leads are used for pacing and sensing functions. Cardioversion and defibrillation pulses (e.g., anti-tachyarrhythmia shocks) are generally applied between a coil electrode carried by one of the leads and the ICD housing, which acts as an active can electrode.

SUMMARY

Artificial pacemakers may adjust cardiac therapy based on the application of defibrillation and/or cardioversion therapy, such as defibrillation and/or cardioversion therapy from an automated external defibrillator (AED) or a subcutaneous ICD. In situations in which a subcutaneous ICD operates in conjunction with a co-implanted artificial pacemaker, such as a leadless pacing device (LPD), it may be important that the pacemaker knows when the subcutaneous ICD has delivered a shock. Based on the knowledge that the shock has been delivered, the pacemaker may, for example, terminate ATP and/or activate post-shock pacing. This disclosure describes the implementation of an anti-tachyarrhythmia shock detector based on the detection of the signal across an electrode pair of the LPD or other pacemaker. A number of additional uses for the detector are also described.

This disclosure includes at least three general techniques for detection of an anti-tachyarrhythmia shock: detection of the relatively high amplitude level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, and detection of a large post-shock polarization change. Each technique looks for a different electrical signal characteristic. Any of the three techniques may be combined to improve sensitivity and/or specificity. For example, an implantable pacing device may combine detection of the high level of an anti-tachyarrhythmia shock combined with one or both of the detection of a high slew rate of the leading and trailing edges, and the detection of a large post-shock polarization change.

In one example, this disclosure is directed to a method for detecting, with an implantable pacemaker, delivery of an anti-tachyarrhythmia shock by another device. The method comprises delivering, by the implantable pacemaker, cardiac stimulation therapy, sensing, by the implantable pacemaker via an electrode pair within the patient, an electrical signal, detecting, by the implantable pacemaker, the anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the electrode pair within the patient, and altering the cardiac stimulation therapy delivered by the implantable pacemaker based on the detected anti-tachyarrhythmia shock.

In another example, this disclosure is directed to an implantable pacing device comprising an electrode pair, a signal generator configured to deliver cardiac stimulation therapy to a heart of a patient, a shock detector configured to sense, from the electrode pair when the implantable medical device is implanted within a patient, an electrical signal, and a processor configured to detect an anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the electrode pair within the patient, and alter the cardiac stimulation therapy based on the detected anti-tachyarrhythmia shock.

In a further example, this disclosure is directed to a system comprising a subcutaneous implantable cardioverter defibrillator comprising a first set of electrodes and configured to sense a first electrical signal from a heart of a patient via the one or more first electrodes, detect a tachyarrhythmia within the sensed first electrical signal, and determine, based on the detected tachyarrhythmia, to deliver anti-tachyarrhythmia shock therapy to the patient to treat the detected arrhythmia. The system further includes a leadless pacing device configured to be implanted within the heart of the patient. The leadless pacing device comprises a second set of electrodes, a signal generator configured to deliver stimulation therapy to the heart of the patient, a shock detector configured to sense, from the second set of electrodes when the leadless pacing device is implanted within a patient, an electrical signal, and a processor configured to detect an anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the second set of electrodes within the patient, and alter the cardiac stimulation therapy based on the detected anti-tachyarrhythmia shock.

The details of one or more examples are set forth in the accompanying drawings and the description below. Other features, objects, and advantages will be apparent from the description and drawings, and from the claims.

BRIEF DESCRIPTION OF DRAWINGS

FIG. **1** is a conceptual drawing illustrating an example system that includes a subcutaneous implantable cardioverter defibrillator (ICD) implanted exterior to the rib cage of a

patient and a leadless pacing device (LPD) implanted within a cardiac chamber of the patient.

FIG. **2** is a conceptual drawing illustrating the example LPD of FIG. **1**.

FIG. **3** is a functional block diagram illustrating an example configuration of the LPD of FIG. **1**.

FIG. **4** is a functional block diagram illustrating an example configuration of the subcutaneous ICD of FIG. **1**.

FIG. **5**A and FIG. **5**B illustrate defibrillation pulse examples from two different defibrillators. The examples may be representative of defibrillation pulses from both ICDs and AEDs.

FIG. **6**A is a functional block diagram illustrating an example of an anti-tachyarrhythmia shock signal edge detector, whereas FIG. **6**B illustrates an anti-tachyarrhythmia shock signal edge detector output waveform during an anti-tachyarrhythmia shock.

FIG. **7**A is a functional block diagram illustrating an example of an anti-tachyarrhythmia shock amplitude detector, whereas FIG. **7**B illustrates an anti-tachyarrhythmia shock amplitude detector output waveform during an anti-tachyarrhythmia shock.

FIG. **8** is a functional block diagram illustrating an example of an anti-tachyarrhythmia shock polarization detector, which may be effective at detecting defibrillation events that occur during pace blanking.

FIGS. **9**A-**9**C illustrate examples of defibrillation pulse polarization resulting from a defibrillation pulse occurring on or shortly after a pacing pulse.

FIG. **10** illustrates an example waveform of biphasic cardiac pacing including a pacing pulse having two windows separated by a period of substantially no stimulation, the period of no stimulation being suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock.

FIG. **11** illustrates an example waveform of biphasic cardiac pacing including a pacing pulse having three pacing windows separated by two periods of substantially no stimulation, the periods of no stimulation being suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock.

FIG. **12** illustrates an example waveform of biphasic cardiac pacing including a pacing pulse having multiple pacing windows separated by periods of substantially no stimulation, the periods of no stimulation being suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock.

FIG. **13** illustrates an example waveform of monophasic cardiac pacing including a pacing pulse having two windows separated by a period of substantially no stimulation, the period of no stimulation being suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock.

FIG. **14** is a flow diagram of an example process for detecting an anti-tachyarrhythmia shock and delivering post-shock therapy by an implantable pacing device, such as an LPD.

FIG. **15**A illustrates an example circuit that provides analog shock signal detection suitable for inclusion as part of an anti-tachyarrhythmia shock detector.

FIG. **15**B illustrates an example circuit that provides digital shock signal detection suitable for inclusion as part of an anti-tachyarrhythmia shock detector.

DETAILED DESCRIPTION

FIG. **1** is a conceptual drawing illustrating an example cardiac system **10** implanted within a patient **14**. Cardiac system **10** includes a subcutaneous ICD system **30** implanted above the ribcage and sternum and a leadless cardiac pacing device (LPD) **16** implanted within a heart **18** of patient **14**.

Subcutaneous ICD system **30** includes an implantable cardiac defibrillator (ICD) **20** connected to at least one implantable cardiac defibrillation lead **22**. ICD **20** is configured to deliver high-energy cardioversion or defibrillation pulses to a patient's heart when atrial or ventricular fibrillation is detected. Cardioversion shocks are typically delivered in synchrony with a detected R-wave when fibrillation detection criteria are met. Defibrillation pulses are typically delivered when fibrillation criteria are met, and the R-wave cannot be discerned from signals sensed by ICD **20**.

ICD **20** of FIG. **1** is implanted subcutaneously on the left side of patient **14** above the ribcage. Defibrillation lead **22** extends subcutaneously above the ribcage from ICD **20** toward a center of the torso of patient **14**, bends or turns near the center of the torso, and extends subcutaneously superior above the ribcage and/or sternum. Defibrillation lead **22** may be offset laterally to the left or the right of the sternum or located over the sternum. Defibrillation lead **22** may extend substantially parallel to the sternum or be angled lateral from the sternum at either the proximal or distal end.

In other instances, lead **22** may be implanted at other extravascular locations. For example, lead **22** may be implanted at least partially in a substernal location, e.g., between the ribcage and/or sternum and heart. In one such configuration, a proximal portion of lead **22** extends subcutaneously from ICD **20** toward the sternum and a distal portion of lead **22** extends superior under or below the sternum in the anterior mediastinum. The anterior mediastinum is bounded laterally by the pleurae, posteriorly by the pericardium, and anteriorly by the sternum. In some instances, the anterior wall of the anterior mediastinum may also be formed by the transversus thoracis and one or more costal cartilages. The anterior mediastinum includes a quantity of loose connective tissue (such as areolar tissue), some lymph vessels, lymph glands, substernal musculature (e.g., transverse thoracic muscle), branches of the internal thoracic artery, and the internal thoracic vein. In one example, the distal portion of lead **22** extends along the posterior side of the sternum substantially within the loose connective tissue and/or substernal musculature of the anterior mediastinum. Lead **22** may be at least partially implanted in other intrathoracic locations, e.g., other non-vascular, extra-pericardial locations, including the gap, tissue, or other anatomical features around the perimeter of and adjacent to, but not attached to, the pericardium or other portion of the heart and not above the sternum or ribcage.

Defibrillation lead **22** includes an insulative lead body having a proximal end that includes a connector configured to be connected to ICD **20** and a distal portion that includes one or more electrodes. Defibrillation lead **22** also includes one or more conductors that form an electrically conductive path within the lead body and interconnect the electrical connector and respective ones of the electrodes.

Defibrillation lead **22** includes a defibrillation electrode **24** toward the distal portion of defibrillation lead **22**, e.g., toward the portion of defibrillation lead **22** extending along the sternum. Defibrillation lead **22** is placed along sternum such that a therapy vector between defibrillation electrode **24** and a housing electrode formed by or on ICD **20** (or other second electrode of the therapy vector) is substantially across a ventricle of heart **18**. The therapy vector may, in one example, be viewed as a line that extends from a point on defibrillation electrode **24** (e.g., a center of the defibrillation electrode **24**)

to a point on the housing electrode of ICD **20**. Defibrillation electrode **24** may, in one example, be an elongated coil electrode.

Defibrillation lead **22** may also include one or more sensing electrodes, such as sensing electrodes **26** and **28**, located along the distal portion of defibrillation lead **22**. In the example illustrated in FIG. **1**, sensing electrodes **26** and **28** are separated from one another by defibrillation electrode **24**. In other examples, however, sensing electrodes **26** and **28** may be both distal of defibrillation electrode **24** or both proximal of defibrillation electrode **24**. In other examples, lead **22** may include more or fewer electrodes at various locations proximal and/or distal to defibrillation electrode **24**. In the same or different examples, ICD **20** may include one or more electrodes on another lead (not shown).

ICD system **30** may sense electrical signals via one or more sensing vectors that include combinations of electrodes **26** and **28** and the housing electrode of ICD **20**. For example, ICD **20** may obtain electrical signals sensed using a sensing vector between electrodes **26** and **28**, obtain electrical signals sensed using a sensing vector between electrode **26** and the conductive housing electrode of ICD **20**, obtain electrical signals sensed using a sensing vector between electrode **28** and the conductive housing electrode of ICD **20**, or a combination thereof. In some instances, ICD **20** may even sense cardiac electrical signals using a sensing vector that includes defibrillation electrode **24** and one of sensing electrodes **26** and **28** or the housing electrode of ICD **20**.

The sensed electrical intrinsic signals may include electrical signals generated by cardiac muscle and indicative of depolarizations and repolarizations of heart **18** at various times during the cardiac cycle. Additionally, the sensed electrical signals may also include electrical signals, e.g., pacing pulses, generated and delivered to heart **18** by LPD **16**. ICD **20** analyzes the electrical signals sensed by the one or more sensing vectors to detect tachyarrhythmia, such as ventricular tachycardia or ventricular fibrillation. In response to detecting the tachycardia, ICD **20** may begin to charge a storage element, such as a bank of one or more capacitors, and, when charged, deliver one or more defibrillation pulses via defibrillation electrode **24** of defibrillation lead **22** if the tachyarrhythmia is still present.

In the example of FIG. **1**, LPD **16** is implanted within right ventricle of heart **18** to sense electrical activity of heart **18** and deliver pacing therapy, e.g., anti-tachycardia pacing (ATP) therapy, bradycardia pacing therapy, and/or post-shock pacing, to heart **18**. LPD **16** may be attached to an interior wall of the right ventricle of heart **18** via one or more fixation elements that penetrate the tissue. These fixation elements may secure LPD **16** to the cardiac tissue and retain an electrode (e.g., a cathode or an anode) in contact with the cardiac tissue. However, in other examples, system **10** may include additional pacing devices **16** within respective chambers of heart **18** (e.g., right or left atrium and/or left ventricle). In further examples, LPD **16** may be attached to an external surface of heart **18** (e.g., in contact with the epicardium) such that LPD **16** is disposed outside of heart **18**.

LPD **16** may be capable sensing electrical signals using the electrodes carried on the housing of LPD **16**. These electrical signals may be electrical signals generated by cardiac muscle and indicative of depolarizations and repolarizations of heart **18** at various times during the cardiac cycle. LPD **16** may analyze the sensed electrical signals to detect tachyarrhythmias, such as ventricular tachycardia or ventricular fibrillation. In response to detecting the tachyarrhythmia, LPD **16** may, e.g., depending on the type of tachyarrhythmia, begin to deliver ATP therapy via the electrodes of LPD **16**. In addition to or instead of ATP therapy, LPD **16** may also deliver bradycardia pacing therapy and post-shock pacing.

Cardiac LPD **16** and subcutaneous ICD system **30** may be configured to operate completely independent of one another. In such a case, LPD **16** and subcutaneous ICD system **30** are not capable of establishing telemetry communication sessions with one another to exchange information about sensing and/or therapy using one-way or two-way communication. Instead, each of LPD **16** and subcutaneous ICD system **30** analyze the data sensed via their respective electrodes to make tachyarrhythmia detection and/or therapy decisions. As such, each device does not know if the other will detect the tachyarrhythmia, if or when it will provide therapy, and the like.

During a tachyarrhythmia that could be treated with either ATP or a defibrillation pulse, it is important to ensure that ATP therapies do not overlap or take place after the defibrillation pulse. Applying ATP after a defibrillation pulse could be pro-arrhythmic and present a hazard to the patient. Moreover, it would be desirable for LPD **16** to deliver post-shock pacing after delivery of a cardioversion/defibrillation pulse. Systems could be designed to provide device-to-device communication between subcutaneous ICD system **30** and LPD **16**, but this may add complexity to the system and not be highly effective or fast enough to prevent unwanted ATP therapies post defibrillation pulse or too slow to initiate post-shock pacing therapies. The shock detection techniques described herein, however, improve the coordination of therapy between subcutaneous ICD **20** and LPD **16** without requiring device-to-device communication.

Although FIG. **1** is described in the context of a subcutaneous ICD system **30** and a LPD **16**, the techniques may be applicable to other coexistent systems. For example, an ICD system that includes a lead having a distal portion that is implanted at least partially under the sternum (or other extra-pericardial location) instead of being implanted above the ribs and/or sternum. As another example, instead of a leadless pacing device, a pacing system may be implanted having a pacemaker and one or more leads connected to and extending from the pacemaker into one or more chambers of the heart or attached to the outside of the heart to provide pacing therapy to the one or more chambers. As such, the example of FIG. **1** is illustrated for exemplary purposes only and should not be considered limiting of the techniques described herein.

External programmer **21** may be configured to communicate with one or both of subcutaneous ICD system **30** and LPD **16**. In examples where external programmer **21** only communicates with one of subcutaneous ICD system **30** and LPD **16**, the non-communicative device may receive instructions from or transmit data to the device in communication with programmer **21**. In some examples, programmer **21** comprises a handheld computing device, computer workstation, or networked computing device. Programmer **21** may include a user interface that receives input from a user. In other examples, the user may also interact with programmer **21** remotely via a networked computing device. The user may interact with programmer **21** to communicate with LPD **16** and/or subcutaneous ICD system **30**. For example, the user may interact with programmer **21** to send an interrogation request and retrieve therapy delivery data, update therapy parameters that define therapy, manage communication between LPD **16** and/or subcutaneous ICD system **30**, or perform any other activities with respect to LPD **16** and/or subcutaneous ICD system **30**. Although the user is a physician, technician, surgeon, electrophysiologist, or other healthcare professional, the user may be patient **14** in some examples.

Programmer **21** may also allow the user to define how LPD **16** and/or subcutaneous ICD system **30** senses electrical signals (e.g., ECGs), detects arrhythmias such as tachyarrhythmias, delivers therapy, and communicates with other devices of system **10**. For example, programmer **21** may be used to change tachyarrhythmia detection parameters. In another example, programmer **21** may be used to manage therapy parameters that define therapies such as anti-tachyarrhythmia shocks and/or ATP. Moreover, programmer **21** may be used to alter communication protocols between LPD **16** and subcutaneous ICD system **30**. For example, programmer **21** may instruct LPD **16** and/or subcutaneous ICD system **30** to switch between one-way and two-way communication and/or change which of LPD **16** and/or subcutaneous ICD system **30** are tasked with initial detection of arrhythmias.

Programmer **21** may communicate with LPD **16** and/or subcutaneous ICD system **30** via wireless communication using any techniques known in the art. Examples of communication techniques may include, for example, proprietary and non-proprietary radiofrequency (RF) telemetry, but other techniques are also contemplated. In some examples, programmer **21** may include a programming head that may be placed proximate to the patient's body near the LPD **16** and/or subcutaneous ICD system **30** implant site in order to improve the quality or security of communication between LPD **16** and/or subcutaneous ICD system **30** and programmer **21**.

LPD **16** may be configured to adjust cardiac therapy based on the application of anti-tachyarrhythmia shock therapy by ICD **20**. It is important that LPD **16** knows when ICD **20** has delivered tachyarrhythmia shock therapy. In response to the delivery of the shock, the LPD may terminate ATP and activate post-shock pacing.

In some examples, LPD **16** and subcutaneous ICD system **30** may engage in communication to facilitate the appropriate detection of arrhythmias and/or delivery of anti-tachycardia therapy. Anti-tachycardia therapy may include anti-tachyarrhythmia shocks (e.g., cardioversion or defibrillation pulses) and/or anti-tachycardia pacing (ATP). The communication may include one-way communication in which one device is configured to transmit communication messages and the other device is configured to receive those messages. The communication may instead include two-way communication in which each device is configured to transmit and receive communication messages. Although the examples below describe detection of tachyarrhythmias and the delivery of anti-tachyarrhythmia shocks and/or ATP, LPD **16** and subcutaneous ICD system **30** may be configured to communicate with each other and provide alternative electrical stimulation therapies. Two-way communication and coordination of the delivery of patient therapies between LPD **16** and subcutaneous ICD system **30** is described in commonly-assigned U.S. patent application Ser. No. 13/756,085, titled, "SYSTEMS AND METHODS FOR LEADLESS PACING AND SHOCK THERAPY," filed Jan. 31, 2013, the entire content of which is incorporated by reference herein.

In combination with, or as an alternative to, communication between LPD **16** and subcutaneous ICD system **30**, LPD **16** may be configured to detect an anti-tachyarrhythmia shock delivered by subcutaneous ICD system **30** or an external defibrillator according to the detection of an electrical signal across two or more electrodes of LPD **16**. LPD **16** may be configured to detect an anti-tachyarrhythmia shock based on electrical characteristics of the anti-tachyarrhythmia shock. Even though different defibrillation devices may provide different waveforms, including different pulse durations and amplitudes, defibrillation pulses generally have electrical signal characteristics such that detection of an anti-tachyarrhythmia shock can occur even without prior knowledge as to an anti-tachyarrhythmia shock waveform of an implanted or external defibrillator. In this manner, LPD **16** may coordinate the delivery of cardiac stimulation therapy, including the termination of ATP and the initiation of the delivery of post-shock pacing, with the application of an anti-tachyarrhythmia shock merely through the detection of defibrillation pulses and without the need to communicate with the defibrillation device applying the anti-tachyarrhythmia shock.

In some examples, LPD **16** detects the anti-tachyarrhythmia shock by measuring the voltage across the electrode inputs of the implanted device. LPD **16** may detect one or more signal characteristics of an anti-tachyarrhythmia shock including: detection of the high amplitude level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, and detection of a large post-shock polarization change. Detection of more than one signal characteristic may improve sensitivity and/or specificity. For example, LPD **16** may detect a high level of an anti-tachyarrhythmia shock in combination with one or both of the detection of a high slew rate of the leading and trailing edges, and the detection of a large post-shock polarization change.

In one example, LPD **16** may be configured to receive an indication of a detected cardiac arrhythmia eligible for anti-tachyarrhythmia shock therapy. LPD **16** may include a set of electrodes configured to be implanted within or near heart **18** of patient **14**. In response to receiving the indication of the tachyarrhythmia, LPD **16** may enable a shock detector of LPD **16** configured to detect delivery of anti-tachyarrhythmia shock therapy. The shock detector may then detect delivery of anti-tachyarrhythmia shock therapy by measuring the voltage across the electrode inputs (e.g., detect that the shock has been delivered). The shock detector may apply one or more of three general techniques for detection of an anti-tachyarrhythmia shock: detection of the high level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, and detection of a large post-shock polarization change. Each technique looks for a different electrical signal characteristic. The three techniques may be combined to improve sensitivity and/or specificity. For example, the high level of an anti-tachyarrhythmia shock may be combined with one or both of the detection of a high slew rate of the leading and trailing edges, and the detection of a large post-shock polarization change.

In response to detection of the anti-tachyarrhythmia shock, the LPD **16** may abort and/or temporarily suspend the delivery of ATP and to activate post-shock pacing, such as VVI (Ventricular sensing, Ventricular pacing, Inhibited pacing when activity sensed) post-shock pacing. ATP may remain suspended temporarily following an anti-tachyarrhythmia shock to insure that the relatively higher-rate pacing pulses will not induce another arrhythmia. Additionally, post-shock pacing may be used to insure pacing support if the patient's heart does not begin to beat normally immediately following an anti-tachyarrhythmia shock. The pacing device may deliver post-shock pacing with a higher than normal pulse amplitude and pulse width (relative to typical cardiac pacing) to minimize the risk of loss of capture following an anti-tachyarrhythmia shock. A higher capture threshold may occur as a result of tissue stunning due to elevated current in the myocardial tissue from the anti-tachyarrhythmia shock delivery. A higher threshold may also occur as a result of physiological changes in the tissue resulting from lack of blood flow to the myocardium during ventricular fibrillation (VF). Furthermore, after an anti-tachyarrhythmia shock there

can be increased polarization at the lead interface resulting in the need for a higher voltage to overcome the lead polarization.

In one example, LPD **16** may deliver post-shock pacing to heart **18** via at least a subset of the set of electrodes of LPD **16**. In some examples, LPD **16** may deliver the post-shock pacing after entering a post-shock pacing mode in response to detecting the shock. In some examples, LPD **16** may use a timer to determine when a predetermined time has elapsed, during which the shock should have been delivered. LPD **16** may begin post-shock pacing after the predetermined period has elapsed and/or stop post-shock pacing.

LPD **16** may receive the indication of the detected cardiac tachyarrhythmia in a variety of ways. For example, LPD **16** may sense, via at least a subset of the set of electrodes, an electrical signal from heart **18**. LPD **16** may then detect, from the electrical signal, a cardiac tachyarrhythmia eligible for anti-tachyarrhythmia shock therapy. In this manner, LPD **16** may receive the indication of the detected arrhythmia via direct detection of the arrhythmia at LPD **16**. In another example, subcutaneous ICD system **30** may be configured to transmit a communication including the indication to LPD **16**. The indication of the detected arrhythmia may thus be received from subcutaneous ICD system **30**, for example. LPD **16** may receive a communication from subcutaneous ICD system **30** indicating that a cardiac arrhythmia was detected by subcutaneous ICD system **30**. Alternatively, LPD **16** may receive a communication from subcutaneous ICD system **30** indicating that a shock is impending.

Detection of the anti-tachyarrhythmia shock may be used to abort and/or temporarily suspend the delivery of ATP and to activate post-shock pacing, such as VVI post-shock pacing. ATP may be temporarily suspended following an anti-tachyarrhythmia shock to insure that the pacing pulses will not induce another arrhythmia. For example, ATP may be temporarily suspended following an anti-tachyarrhythmia shock until the current arrhythmia has been terminated or until a short period of time has elapsed to prevent interfering with the subcutaneous ICD.

In addition to the delivery of ATP, LPD **16** may be configured to deliver post-shock pacing to heart **18**. After delivery of an anti-tachyarrhythmia shock, heart **18** may benefit from pacing to return to a normal sinus rhythm (e.g., if heart **18** has developed bradycardia or asystole) or otherwise recover from receiving the shock. In some examples, LPD **16** and/or subcutaneous ICD system **30** may be configured to detect bradycardia or asystole. In some examples, this post-shock pacing may be automatically delivered in response to the LPD **16** detecting that a shock was delivered. Post-shock pacing may be used to ensure pacing support if the patient's heart does not begin to beat normally immediately following an anti-tachyarrhythmia shock. A higher than normal amplitude and pulse width is commonly used to minimize the risk of loss of capture following an anti-tachyarrhythmia shock. A higher capture threshold may occur as a result of tissue stunning due to elevated current in the myocardial tissue from the anti-tachyarrhythmia shock delivery. A higher threshold may also occur as a result of physiological changes in the tissue resulting from lack of blood flow to the myocardium during VF. Furthermore, after an anti-tachyarrhythmia shock there can be increased polarization at the lead interface resulting in the need for a higher voltage to overcome the lead polarization.

In some examples, LPD **16** may enable the shock detector when ATP is delivered to heart **18**, in anticipation of a shock. In some examples, LPD **16** may enable the shock detector in response to detecting a fast rate, such as a tachyarrhythmia (e.g., when communication between LPD **16** and subcutaneous ICD system **30** is not present or is unreliable). The tachyarrhythmia may be detected based on sensed electrical signals and/or mechanical signals from heart **18**. In any example, the shock detector may be disabled until an indication of an arrhythmia is terminated or impending shock is received.

LPD **16** may also be configured to disable the shock detector. For example, LPD **16** may be configured to track a period of time following detection of delivery of anti-tachyarrhythmia shock therapy. The period of time may be a predetermined period of time and/or tracked with a timer, for example. LPD **16** may also determine that the period of time exceeds a timeout threshold, and, in response to the determination, disable the shock detector. LPD **16** may disable the shock detector when not needed to conserve battery power, for example.

LPD **16** may also re-start post-shock pacing if additional shocks are detected. For example, LPD **16** may be configured to detect a first shock and begin delivery of the post-shock pacing if needed (e.g., bradycardia or systole has been detected). LPD **16** may subsequently detect the delivery of a second shock, and, in response to the detection of the second shock, re-start delivery of the post-shock pacing if needed. LPD **16** may continue to re-start post-shock pacing as long as additional shocks are delivered. However, LPD **16** may be configured to stop re-starting post-shock pacing after a predetermined number of shocks, or in response to subcutaneous ICD system **30** transmitting a message instructing LPD **16** to stop delivery of post-shock pacing. LPD **16** and/or subcutaneous ICD system **30** may implement an intrinsic beat detector or other algorithm to distinguish between intrinsic beats and potential artifacts caused by pacing and/or shock therapy. LPD **16** may also deliver ATP upon detection of a tachyarrhythmia, and terminate ATP if a defibrillation pulse is detected. LPD **16** may initiate post-shock pacing and/or, upon detection of additional tachyarrhythmia following the shock, resume ATP.

In some examples, LPD **16** may terminate post-shock pacing in response to various indicators. For example, LPD **16** may track a period of time following the start of post-shock pacing. LPD **16** may then determine that the period of time exceeds a timeout threshold. For example, LPD **16** may use a timer to track this period of time. In response to the determination, LPD **16** may terminate delivery of post-shock pacing. In other examples, LPD **16** may terminate post-shock pacing after delivery of a predetermined number of pacing pulses. Alternatively, LPD **16** may terminate post-shock pacing in response to detection of a normal sinus rhythm or receiving a communication from subcutaneous ICD system **30** instructing LPD **16** to terminate post-shock pacing.

Although LPD **16** is generally described as delivering post-shock pacing, in other examples, different implanted devices may provide post-shock pacing. For example, LPD **16** may be configured to deliver ATP, but a different LPD implanted in a different chamber of heart **18** may be configured to detect a shock and deliver the post-shock pacing to heart **18**. In other examples, the implanted device delivering post-shock pacing may not be a leadless pacing device. For example, an implantable pacing device, separate from an ICD delivering the anti-tachyarrhythmia shock, may include one or more leads for delivering post-shock pacing therapy to one or more locations of heart **18**. As another example, an ICD delivering the anti-tachyarrhythmia shock may deliver post-shock pacing, whereas LPD is configured to provide ATP, and not post-shock pacing.

FIG. **2** is a conceptual drawing illustrating example LPD **16** of FIG. **1** that may include a shock detector and/or utilize the shock detection techniques of this disclosure. As shown in FIG. **2**, LPD **16** includes case **50**, cap **58**, electrode **60**, elec-

trode **52**, fixation mechanisms **62**, flange **54**, and opening **56**. Together, case **50** and cap **58** may be considered the housing of LPD **16**. In this manner, case **50** and cap **58** may enclose and protect the various electrical components within LPD **16**. Case **50** may enclose substantially all of the electrical components, and cap **58** may seal case **50** and create the hermetically sealed housing of LPD **16**. Although LPD **16** is generally described as including one or more electrodes, LPD **16** may typically include at least two electrodes (e.g., electrodes **52** and **60**) to deliver an electrical signal (e.g., therapy such as ATP) and/or provide at least one sensing vector.

Electrodes **52** and **60** are carried on the housing created by case **50** and cap **58**. In this manner, electrodes **52** and **60** may be considered leadless electrodes. In the example of FIG. **2**, electrode **60** is disposed on the exterior surface of cap **58**. Electrode **60** may be a circular electrode positioned to contact cardiac tissue upon implantation. Electrode **52** may be a ring or cylindrical electrode disposed on the exterior surface of case **50**. Both case **50** and cap **58** may be electrically insulating. Electrode **60** may be used as a cathode and electrode **52** may be used as an anode, or vice versa, for delivering pacing stimulation therapy such as ATP or post-shock pacing. However, electrodes **52** and **60** may be used in any stimulation configuration. In addition, electrodes **52** and **60** may be used to detect intrinsic electrical signals from cardiac muscle. In other examples, LPD **16** may include three or more electrodes, where each electrode may deliver therapy and/or detect intrinsic signals. ATP delivered by LPD **16**, as compared with alternative devices, may be considered to be "painless" to patient **14** or even undetectable by patient **14** since the electrical stimulation occurs very close to or at cardiac muscle and at relatively low energy levels.

Fixation mechanisms **62** may attach LPD **16** to cardiac tissue. Fixation mechanisms **62** may be active fixation tines, screws, clamps, adhesive members, or any other types of attaching a device to tissue. As shown in the example of FIG. **2**, fixation mechanisms **62** may be constructed of a memory material that retains a preformed shape. During implantation, fixation mechanisms **62** may be flexed forward to pierce tissue and allowed to flex back towards case **50**. In this manner, fixation mechanisms **62** may be embedded within the target tissue.

Flange **54** may be provided on one end of case **50** to enable tethering or extraction of LPD **16**. For example, a suture or other device may be inserted around flange **54** and/or through opening **56** and attached to tissue. In this manner, flange **54** may provide a secondary attachment structure to tether or retain LPD **16** within heart **18** if fixation mechanisms **62** fail. Flange **54** and/or opening **56** may also be used to extract LPD **16** once the LPD needs to be explanted (or removed) from patient **14** if such action is deemed necessary.

The techniques described herein are generally described with regard to a leadless pacing device such as LPD **16**. LPD **16** may be an example of an anti-tachycardia pacing device (ATPD). However, alternative implantable medical devices may be used to perform the same or similar functions as LPD **16** (e.g., delivering ATP to heart **18**) and communicate with subcutaneous ICD system **30**. For example, an ATPD may include a small housing that carries an electrode, similar to LPD **16**, and configured to be implanted within a chamber of heart **18**. The ATPD may also include one or more relatively short leads configured to place one or more respective additional electrodes at another location within the same chamber of the heart or a different chamber of the heart. This configuration may be referred to as an Intercardiac Pacing Device (IPD). In this manner, the housing of the ATPD may not carry all of the electrodes used to deliver ATP or perform other functions. In other examples, each electrode of the ATPD may be carried by one or more leads (e.g., the housing of the ATPD may not carry any of the electrodes).

In another example, the ATPD may be configured to be implanted external to heart **18**, e.g., near or attached to the epicardium of heart **18**. An electrode carried by the housing of the ATPD may be placed in contact with the epicardium and/or one or more electrodes of leads coupled to the ATPD may be placed in contact with the epicardium at locations sufficient to provide therapy such as ATP (e.g., on external surfaces of the left and/or right ventricles). In any example, subcutaneous ICD system **30** may communicate with one or more leadless or leaded devices implanted internal or external to heart **18**.

FIG. **3** is a functional block diagram illustrating an example configuration of LPD **16** of FIG. **1**. In the illustrated example, LPD **16** includes a processor **90**, memory **92**, signal generator **96**, sensing module **98**, shock detector **99**, activity sensor **100**, communication module **94**, and power source **102**. Memory **92** includes computer-readable instructions that, when executed by processor **90**, cause LPD **16** and processor **90** to perform various functions attributed to LPD **16** and processor **90** herein (e.g., detecting arrhythmias, communicating with subcutaneous ICD system **30**, and delivering anti-tachycardia pacing and post-shock pacing as well as conventional brady pacing therapy). Memory **92** may include any volatile, non-volatile, magnetic, optical, or electrical media, such as a random access memory (RAM), read-only memory (ROM), non-volatile RAM (NVRAM), electrically-erasable programmable ROM (EEPROM), flash memory, or any other digital or analog media.

Processor **90** may include any one or more of a microprocessor, a controller, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field-programmable gate array (FPGA), or equivalent discrete or analog logic circuitry. In some examples, processor **90** may include multiple components, such as any combination of one or more microprocessors, one or more controllers, one or more DSPs, one or more ASICs, or one or more FPGAs, as well as other discrete or integrated logic circuitry. The functions attributed to processor **90** herein may be embodied as software, firmware, hardware or any combination thereof.

Processor **90** controls signal generator **96** to deliver stimulation therapy to heart **18** according to therapy parameters, which may be stored in memory **92**. For example, processor **90** may control signal generator **96** to deliver electrical pulses with the amplitudes, pulse widths, frequency, or electrode polarities specified by the therapy parameters. In this manner, signal generator **96** may deliver pacing pulses (e.g., ATP pulses or post-shock pacing therapy, or conventional bradycardia pacing pulses) to heart **18** via electrodes **52** and **60**. Although LPD **16** may only include two electrodes, e.g., electrodes **52** and **60**, LPD **16** may utilize three or more electrodes in other examples. LPD **16** may use any combination of electrodes to deliver therapy and/or detect electrical signals from patient **14**.

Signal generator **96** is electrically coupled to electrodes **52** and **60** carried on the housing of LPD **16**. In the illustrated example, signal generator **96** is configured to generate and deliver electrical stimulation therapy to heart **18**. For example, signal generator **96** may deliver the electrical stimulation therapy to a portion of cardiac muscle within heart **18** via electrodes **52** and **60**. In some examples, signal generator **96** may deliver pacing stimulation, e.g., ATP therapy or post-shock pacing, in the form of voltage or current electrical pulses. In other examples, signal generator **96** may deliver one or more of these types of stimulation in the form of other

signals, such as sine waves, square waves, or other substantially continuous time signals. Although LPD **16** is generally described as delivering pacing pulses, LPD **16** may deliver cardioversion or defibrillation pulses in other examples.

ATP may be delivered to patient **14** as defined by a set of parameters. These parameters may include pulse intervals, pulse width, current and/or voltage amplitudes, and durations for each pacing mode. For example, the pulse interval may be based on a fraction of the detected ventricular tachycardia (VT) cycle length and be between approximately 150 milliseconds and 500 milliseconds (e.g., between approximately 2.0 hertz and 7.0 hertz), and the pulse width may be between approximately 0.5 milliseconds and 2.0 milliseconds. The amplitude of each pacing pulse may be between approximately 2.0 volts and 10.0 volts. In some examples, the pulse amplitude may be approximately 6.0 V and the pulse width may be approximately 1.5 milliseconds; another example may include pulse amplitudes of approximately 5.0 V and pulse widths of approximately 1.0 milliseconds. Each train of pulses during ATP may last for a duration of between approximately 0.5 seconds to approximately 15 seconds or be defined as a specific number of pulses. Each pulse, or burst of pulses, may include a ramp up in amplitude or in pulse rate. In addition, trains of pulses in successive ATP periods may be delivered at increasing pulse rate in an attempt to capture the heart and terminate the tachycardia. Example ATP parameters and other criteria involving the delivery of ATP are described in U.S. Pat. No. 6,892,094 to Ousdigian et al., entitled, "COMBINED ANTI-TACHYCARDIA PACING (ATP) AND HIGH VOLTAGE THERAPY FOR TREATING VENTRICULAR ARRHYTHMIAS," and issued on May 10, 2005, the entire content of which is incorporated herein by reference.

Parameters that define post-shock pacing may also vary. In one example, monophasic post-shock pacing therapy may have a pulse width of approximately 1 milliseconds at each phase and a pulse amplitude of approximately 5 volts. The pacing rate may be set to 30-60 beats per minute (0.5-1 hertz). The duration of each post-shock pacing session may be between 10 seconds and 60 seconds, or even longer in other examples. In other examples, pulse widths, pulse amplitudes, and/or durations of post-shock pacing may be greater or lower.

Signal generator **96** may also include circuitry for measuring the capture threshold of electrodes **52** and **60**. The capture threshold may indicate the voltage and pulse width necessary to induce depolarization of the surrounding cardiac muscle. For example, signal generator **96** may measure the voltage of pacing signals needed to induce ventricular contractions. In examples in which LPD **16** includes more than two electrodes, signal generator **96** may include a switch module and processor **90** may use the switch module to select, e.g., via a data/address bus, which of the available electrodes are used to deliver pacing pulses. The switch module may include a switch array, switch matrix, multiplexer, or any other type of switching device suitable to selectively couple stimulation energy to selected electrodes. In the instance that the capture threshold exceeds useable limits, processor **90** may withhold delivery of ATP or post-shock pacing. In addition, processor **90** may transmit communication to subcutaneous ICD system **30** if pacing cannot be delivered.

Electrical sensing module **98** monitors signals from electrodes **52** and **60** in order to monitor electrical activity of heart **18**, impedance, or other electrical phenomenon. Sensing may be done to determine heart rates or heart rate variability, or to detect arrhythmias (e.g., tachyarrhythmias or bradycardia) or other electrical signals. Sensing module **98** may also include a switch module to select which of the available electrodes (or electrode polarity) are used to sense the heart activity, depending upon which electrode combination, or electrode vector, is used in the current sensing configuration. In examples with several electrodes, processor **90** may select the electrodes that function as sense electrodes, i.e., select the sensing configuration, via the switch module within sensing module **98**. Sensing module **98** may include one or more detection channels, each of which may be coupled to a selected electrode configuration for detection of cardiac signals via that electrode configuration. Some detection channels may be configured to detect cardiac events, such as P- or R-waves, and provide indications of the occurrences of such events to processor **90**, e.g., as described in U.S. Pat. No. 5,117,824 to Keimel et al., which issued on Jun. 2, 1992 and is entitled, "APPARATUS FOR MONITORING ELECTRICAL PHYSIOLOGIC SIGNALS," and is incorporated herein by reference in its entirety. Processor **90** may control the functionality of sensing module **98** by providing signals via a data/address bus.

Processor **90** may include a timing and control module, which may be embodied as hardware, firmware, software, or any combination thereof. The timing and control module may comprise a dedicated hardware circuit, such as an ASIC, separate from other processor **90** components, such as a microprocessor, or a software module executed by a component of processor **90**, which may be a microprocessor or ASIC. The timing and control module may implement programmable counters. If LPD **16** is configured to generate and deliver pacing pulses to heart **18**, such counters may control the basic time intervals associated with DDD, VVI, DVI, VDD, AAI, DDI, DDDR, VVIR, DVIR, VDDR, AAIR, DDIR and other modes of pacing. Example LPDs that may deliver pacing using such modes are described in U.S. patent application Ser. No. 13/665,492 to Bonner et al., entitled, "LEADLESS PACEMAKER SYSTEM," and filed on Oct. 31, 2012, or in U.S. patent application Ser. No. 13/665,601 to Bonner et al., entitled, "LEADLESS PACEMAKER SYSTEM," and filed on Oct. 31, 2012. U.S. patent application Ser. No. 13/665,492 to Bonner et al. and U.S. patent Ser. No. 13/665,601 to Bonner et al. are both incorporated herein by reference in their entireties.

Intervals defined by the timing and control module within processor **90** may include atrial and ventricular pacing escape intervals, refractory periods during which sensed P-waves and R-waves are ineffective to restart timing of the escape intervals, and the pulse widths of the pacing pulses. As another example, the timing and control module may withhold sensing from one or more channels of sensing module **98** for a time interval during and after delivery of electrical stimulation to heart **18**. The durations of these intervals may be determined by processor **90** in response to stored data in memory **92**. The timing and control module of processor **90** may also determine the amplitude of the cardiac pacing pulses.

Interval counters implemented by the timing and control module of processor **90** may be reset upon sensing of R-waves and P-waves with detection channels of sensing module **98**. In examples in which LPD **16** provides pacing, signal generator **96** may include pacer output circuits that are coupled to electrodes **52** and **60**, for example, appropriate for delivery of a bipolar or unipolar pacing pulse to one of the chambers of heart **18**. In such examples, processor **90** may reset the interval counters upon the generation of pacing pulses by signal generator **96**, and thereby control the basic timing of cardiac pacing functions, including ATP or post-shock pacing.

The value of the count present in the interval counters when reset by sensed R-waves and P-waves may be used by processor **90** to measure the durations of R-R intervals, P-P intervals, P-R intervals and R-P intervals, which are measurements that may be stored in memory **92**. Processor **90** may use the count in the interval counters to detect a tachyarrhythmia event, such as atrial fibrillation (AF), atrial tachycardia (AT), VF, or VT. These intervals may also be used to detect the overall heart rate, ventricular contraction rate, and heart rate variability. A portion of memory **92** may be configured as a plurality of recirculating buffers, capable of holding series of measured intervals, which may be analyzed by processor **90** in response to the occurrence of a pace or sense interrupt to determine whether the patient's heart **18** is presently exhibiting atrial or ventricular tachyarrhythmia.

In some examples, an arrhythmia detection method may include any suitable tachyarrhythmia detection algorithms. In one example, processor **90** may utilize all or a subset of the rule-based detection methods described in U.S. Pat. No. 5,545,186 to Olson et al., entitled, "PRIORITIZED RULE BASED METHOD AND APPARATUS FOR DIAGNOSIS AND TREATMENT OF ARRHYTHMIAS," which issued on Aug. 13, 1996, or in U.S. Pat. No. 5,755,736 to Gillberg et al., entitled, "PRIORITIZED RULE BASED METHOD AND APPARATUS FOR DIAGNOSIS AND TREATMENT OF ARRHYTHMIAS," which issued on May 26, 1998. U.S. Pat. No. 5,545,186 to Olson et al. U.S. Pat. No. 5,755,736 to Gillberg et al. is incorporated herein by reference in their entireties. However, other arrhythmia detection methodologies, such as those methodologies that utilize timing and morphology of the electrocardiogram, may also be employed by processor **90** in other examples.

In some examples, processor **90** may determine that tachyarrhythmia has occurred by identification of shortened R-R (or P-P) interval lengths. Generally, processor **90** detects tachycardia when the interval length falls below 220 milliseconds and fibrillation when the interval length falls below 180 milliseconds. In other examples, processor **70** may detect ventricular tachycardia when the interval length falls between 330 milliseconds and ventricular fibrillation when the interval length falls below 240 milliseconds. These interval lengths are merely examples, and a user may define the interval lengths as desired, which may then be stored within memory **92**. This interval length may need to be detected for a certain number of consecutive cycles, for a certain percentage of cycles within a running window, or a running average for a certain number of cardiac cycles, as examples. In other examples, additional physiological parameters may be used to detect an arrhythmia. For example, processor **90** may analyze one or more morphology measurements, impedances, or any other physiological measurements to determine that patient **14** is experiencing a tachyarrhythmia.

In the event that an ATP regimen is desired, timing intervals for controlling the generation of ATP therapies by signal generator **96** may be loaded by processor **90** into the timing and control module to control the operation of the escape interval counters therein and to define refractory periods during which detection of R-waves and P-waves is ineffective to restart the escape interval counters for the ATP. An ATP regimen may be desired if processor **90** detects an atrial or ventricular tachyarrhythmia based on signals from sensing module **98**, and/or receives a command from another device or system, such as subcutaneous ICD system **30**, as examples.

In addition to detecting and identifying specific types of cardiac rhythms, sensing module **98** may also sample the detected intrinsic signals to generate an electrogram or other time-based indication of cardiac events. Processor **90** may also be able to coordinate the delivery of pacing pulses from different LPDs implanted in different chambers of heart **18**, such as an LPD implanted in atrium and/or an LPD implanted in left ventricle. For example, processor **90** may identify delivered pulses from other LPDs via sensing module **98** and update pulse timing to accomplish a selected pacing regimen. This detection may be on a pulse-to-pulse or beat-to-beat basis, or on a less frequent basis to make slight modifications to pulse rate over time. In other examples, LPDs may communicate with each other via communication module **94** and/or instructions over a carrier wave (such as a stimulation waveform). In this manner, ATP or post-shock pacing may be coordinated from multiple LPDs.

Shock detector **99** may be used to detect anti-tachyarrhythmia shocks delivered by subcutaneous ICD system **30** or another device. For example, processor **90** may enable shock detector **99** in response to detecting a tachyarrhythmia or receiving a communication indicating that an arrhythmia has been detected or a shock is imminent. Processor **90** may also disable shock detector **99** after a predetermined time period has elapsed or when a shock is otherwise not (or no longer) anticipated. When shock detector **99** is enabled, shock detector **99** may identify when an electrical signal received by sensing module **98** is representative of a cardioversion or defibrillation pulse.

In response to detecting a shock via shock detector **99**, processor **90** may begin post-shock pacing when such functionality has been enabled for therapy. Processor **90** may also re-start post-shock pacing in response to detecting additional shocks via shock detector **99**. In some examples, processor **90** may terminate ATP upon detection of a shock.

Shock detector **99** may detect an anti-tachyarrhythmia shock, e.g., a defibrillation or cardioversion pulse, delivered by subcutaneous ICD system **30** or an external defibrillator based on the detection of an electrical signal across two or more electrodes. In order to detect the anti-tachyarrhythmia shock, shock detector **99** may detect one or more signal characteristics of an anti-tachyarrhythmia shock including: detection of the high amplitude level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, and detection of a large post-shock polarization change. Detection of more than one signal characteristic may improve sensitivity and/or specificity of the shock anti-tachyarrhythmia shock detection. For example, shock detector **99** may detect a high level of an anti-tachyarrhythmia shock in combination with one or both of the detection of a high slew rate of the leading and trailing edges and/or the detection of a large post-shock polarization change.

Memory **92** may be configured to store a variety of operational parameters, therapy parameters, sensed and detected data, and any other information related to the therapy and treatment of patient **14**. In the example of FIG. **3**, memory **92** may store sensed ECGs, detected arrhythmias, communications from subcutaneous ICD system **30**, and therapy parameters that define ATP and/or post-shock pacing regimens. In other examples, memory **92** may act as a temporary buffer for storing data until it can be uploaded to subcutaneous ICD system **30**, another implanted device, or programmer **21**.

Activity sensor **100** may be contained within the housing of LPD **16** and include one or more accelerometers or other devices capable of detecting motion and/or position of LPD **16**. For example, activity sensor **100** may include a 3-axis accelerometer that is configured to detect accelerations in any direction in space. Specifically, the 3-axis accelerator may be used to detect LPD **16** motion that may be indicative of cardiac events and/or noise. For example, processor **16** may monitor the accelerations from activity sensor **100** to confirm

or detect arrhythmias. Since LPD **16** may move with a chamber wall of heart **18**, the detected changes in acceleration may also be indicative of contractions. Therefore, LPD **16** may be configured to identify heart rates and confirm arrhythmias, such as a tachycardia, sensed via sensing module **98**.

Communication module **94** includes any suitable hardware, firmware, software or any combination thereof for communicating with another device, such as programmer **21** or subcutaneous ICD system **30** (FIG. **1**). Under the control of processor **90**, communication module **94** may receive downlink telemetry from and send uplink telemetry to programmer **21** with the aid of an antenna, which may be internal and/or external. Processor **90** may provide the data to be uplinked to programmer **21** and the control signals for the telemetry circuit within communication module **94**, e.g., via an address/data bus. In some examples, communication module **94** may provide received data to processor **90** via a multiplexer.

In some examples, LPD **16** may signal programmer **21** to further communicate with and pass the alert through a network such as the Medtronic CareLink® Network developed by Medtronic, Inc., of Minneapolis, Minn., or some other network linking patient **14** to a clinician. LPD **16** may spontaneously transmit information to the network or in response to an interrogation request from a user.

Power source **102** may be any type of device that is configured to hold a charge to operate the circuitry of LPD **16**. Power source **102** may be provided as a rechargeable or non-rechargeable battery. In other example, power source **102** may incorporate an energy scavenging system that stores electrical energy from movement of LPD **16** within patient **14**.

FIG. **4** is a functional block diagram illustrating an example configuration of subcutaneous ICD system **30** of FIG. **1**. In the illustrated example, subcutaneous ICD system **30** includes a processor **70**, memory **72**, shock module **75**, signal generator **76**, sensing module **78**, communication module **80**, activity sensor **82**, and power source **84**. Memory **72** includes computer-readable instructions that, when executed by processor **70**, cause subcutaneous ICD system **30** and processor **70** to perform various functions attributed to subcutaneous ICD system **30** and processor **70** herein (e.g., detection of tachyarrhythmias, communication with LPD **16**, and/or delivery of anti-tachyarrhythmia shock therapy). Memory **72** may include any volatile, non-volatile, magnetic, optical, or electrical media, such as a random access memory (RAM), read-only memory (ROM), non-volatile RAM (NVRAM), electrically-erasable programmable ROM (EEPROM), flash memory, or any other digital or analog media.

Processor **70** may include any one or more of a microprocessor, a controller, a digital signal processor (DSP), an application specific integrated circuit (ASIC), a field-programmable gate array (FPGA), or equivalent discrete or analog logic circuitry. In some examples, processor **70** may include multiple components, such as any combination of one or more microprocessors, one or more controllers, one or more DSPs, one or more ASICs, or one or more FPGAs, as well as other discrete or integrated logic circuitry. The functions attributed to processor **70** herein may be embodied as software, firmware, hardware or any combination thereof.

Processor **70** controls signal generator **76** to deliver stimulation therapy to heart **18** according to therapy parameters, which may be stored in memory **72**. For example, processor **70** may control signal generator **76** to deliver electrical pulses (e.g., shock pulses) with the amplitudes, pulse widths, frequency, or electrode polarities specified by the therapy parameters. In this manner, signal generator **76** may deliver electrical pulses to heart **18** via electrodes **24** and the conductive housing electrode **31** of ICD **20**. In addition, via any combination of electrodes, **24**, **26**, **28** and/or housing **31** may be connected to sensing module **78**. In further examples, signal generator **76** may deliver electrical pulses to heart **18** via any combination of electrodes, **24**, **26**, **28** and/or housing **31**, although electrodes **26** and **28**, may more frequently be used for sensing. Subcutaneous ICD system **30** may use any combination of electrodes to deliver anti-tachycardia therapy and/or detect electrical signals from patient **14**. However, in general, coil electrode **24** and housing **31** may be used to deliver an anti-tachyarrhythmia shock.

Signal generator **76** may also include shock module **75**. Shock module **75** may include circuitry and/or capacitors required to deliver an anti-tachyarrhythmia shock. For example, signal generator **76** may charge shock module **75** to prepare for delivering a shock. Shock module **75** may then discharge to enable signal generator **76** to deliver the shock to patient **14** via one or more electrodes. In other examples, shock module **75** may be located within subcutaneous ICD system **30** but outside of signal generator **76**.

Signal generator **76** is electrically coupled to electrodes **24**, **26**, and **28**. In the illustrated example, signal generator **76** is configured to generate and deliver electrical anti-tachyarrhythmia shock therapy to heart **18**. For example, signal generator **76** may, using shock module **75**, deliver shocks to heart **18** via a subset of electrodes **24**, **26**, and **28**. In some examples, signal generator **76** may deliver pacing stimulation (e.g., post-shock pacing), and cardioversion or defibrillation pulses in the form of voltage or current electrical pulses. In other examples, signal generator **76** may deliver one or more of these types of stimulation or shocks in voltage or current in the form of other signals, such as sine waves, square waves, or other substantially continuous time signals.

Signal generator **76** may include a switch module and processor **70** may use the switch module to select, e.g., via a data/address bus, which of the available electrodes are used to deliver shock and/or pacing pulses. The switch module may include a switch array, switch matrix, multiplexer, or any other type of switching device suitable to selectively couple stimulation energy to selected electrodes.

Electrical sensing module **78** may be configured to monitor signals from at least two of the electrodes **24**, **26**, **28** and housing **31** in order to monitor electrical activity of heart **18**, impedance, or other electrical phenomenon. Sensing may be done to determine heart rates or heart rate variability, or to detect arrhythmias (e.g., tachyarrhythmia) or other electrical signals. Sensing module **78** may also include a switch module to select which of the available electrodes are used to sense the heart activity, depending upon which electrode combination, or electrode vector, is used in the current sensing configuration. In examples with several electrodes, processor **70** may select the electrodes that function as sense electrodes, i.e., select the sensing configuration, via the switch module within sensing module **78**. Sensing module **78** may include one or more detection channels, each of which may be coupled to a selected electrode configuration for detection of cardiac signals via that electrode configuration. Some detection channels may be configured to detect cardiac events, such as P- or R-waves, and provide indications of the occurrences of such events to processor **70**, e.g., as described in U.S. Pat. No. 5,117,824 to Keimel et al., which issued on Jun. 2, 1992 and is entitled, "APPARATUS FOR MONITORING ELECTRICAL PHYSIOLOGIC SIGNALS," and is incorporated herein by reference in its entirety. Processor **70** may control the functionality of sensing module **78** by providing signals via a data/address bus.

Processor **70** may include a timing and control module, which may be embodied as hardware, firmware, software, or any combination thereof. The timing and control module may comprise a dedicated hardware circuit, such as an ASIC, separate from other processor **70** components, such as a microprocessor, or a software module executed by a component of processor **70**, which may be a microprocessor or ASIC. The timing and control module may implement programmable counters. If subcutaneous ICD system **30** is configured to generate and deliver pacing pulses to heart **18**, such counters may control the basic time intervals associated with DDD, VVI, DVI, VDD, AAI, DDI, DDDR, VVIR, DVIR, VDDR, AAIR, DDIR and other modes of pacing.

Intervals defined by the timing and control module within processor **70** may include atrial and ventricular pacing escape intervals, refractory periods during which sensed P-waves and R-waves are ineffective to restart timing of the escape intervals, and the pulse widths of the pacing pulses. As another example, the timing and control module may withhold sensing from one or more channels of sensing module **78** for a time interval during and after delivery of electrical stimulation to heart **18**. The durations of these intervals may be determined by processor **70** in response to stored data in memory **72**. The timing and control module of processor **70** may also determine the amplitude of the cardiac pacing pulses.

Interval counters implemented by the timing and control module of processor **70** may be reset upon sensing of R-waves and P-waves with detection channels of sensing module **78**. The value of the count present in the interval counters when reset by sensed R-waves and P-waves may be used by processor **70** to measure the durations of R-R intervals, P-P intervals, P-R intervals and R-P intervals, which are measurements that may be stored in memory **72**. Processor **70** may use the count in the interval counters to detect a tachyarrhythmia event, such as AF, AT, VF, or VT. These intervals may also be used to detect the overall heart rate, ventricular contraction rate, and heart rate variability. A portion of memory **72** may be configured as a plurality of recirculating buffers, capable of holding series of measured intervals, which may be analyzed by processor **70** in response to the occurrence of a pace or sense interrupt to determine whether the patient's heart **18** is presently exhibiting atrial or ventricular tachyarrhythmia.

In some examples, an arrhythmia detection method may include any suitable tachyarrhythmia detection algorithms. In one example, processor **70** may utilize all or a subset of the rule-based detection methods described in U.S. Pat. No. 5,545,186 to Olson et al., entitled, "PRIORITIZED RULE BASED METHOD AND APPARATUS FOR DIAGNOSIS AND TREATMENT OF ARRHYTHMIAS," which issued on Aug. 13, 1996, or in U.S. Pat. No. 5,755,736 to Gillberg et al., entitled, "PRIORITIZED RULE BASED METHOD AND APPARATUS FOR DIAGNOSIS AND TREATMENT OF ARRHYTHMIAS," which issued on May 26, 1998. U.S. Pat. No. 5,545,186 to Olson et al. U.S. Pat. No. 5,755,736 to Gillberg et al. is incorporated herein by reference in their entireties. However, other arrhythmia detection methodologies, such as those methodologies that utilize timing and morphology of the electrocardiogram, may also be employed by processor **70** in other examples.

In some examples, processor **70** may determine that tachyarrhythmia has occurred by identification of shortened R-R (or P-P) interval lengths. Generally, processor **70** detects tachycardia when the interval length falls below 220 milliseconds and fibrillation when the interval length falls below 180 milliseconds. In other examples, processor **70** may detect ventricular tachycardia when the interval length falls between 330 milliseconds and ventricular fibrillation when the interval length falls between 240 milliseconds. These interval lengths are merely examples, and a user may define the interval lengths as desired, which may then be stored within memory **72**. This interval length may need to be detected for a certain number of consecutive cycles, for a certain percentage of cycles within a running window, or a running average for a certain number of cardiac cycles, as examples.

In the event that processor **70** detects an atrial or ventricular tachyarrhythmia based on signals from sensing module **78**, and an anti-tachyarrhythmia pacing regimen is desired, timing intervals for controlling the generation of anti-tachyarrhythmia pacing therapies by signal generator **76** may be loaded by processor **70** into the timing and control module to control the operation of the escape interval counters therein and to define refractory periods during which detection of R-waves and P-waves is ineffective to restart the escape interval counters for the an anti-tachyarrhythmia pacing. In addition to detecting and identifying specific types of cardiac rhythms, sensing module **78** may also sample the detected intrinsic signals to generate an electrogram or other time-based indication of cardiac events.

In some examples, communication module **80** may be used to detect communication signals from LPD **16**. Instead, LPD **16** may generate electrical signals via one or more electrodes with amplitudes and/or patterns representative of information to be sent to subcutaneous ICD system **30**. The electrical signals may be carried by pacing pulses or separate communication signals configured to be detected by subcutaneous ICD system **30**. In this manner, communication module **80** may be configured to monitor signals sensed by sensing module **78** and determine when a communication message is received from LPD **16**.

In other examples, subcutaneous ICD system **30** may also transmit communication messages to LPD **16** using electrical signals transmitted from one or more of electrodes **24**, **26**, **28** and housing **31**. In this case, communication module **80** may be coupled to signal generator **76** to control the parameters of generated electrical signals or pulses. Alternatively, processor **70** may detect communications via sensing module **78** and/or generate communications for deliver via signal generator **76**. Although communication module **80** may be used to communicate using electrical signals via electrodes **24**, **26**, **28** and housing **31**, communication module **80** may alternatively or in addition use wireless protocols, such as RF telemetry, to communicate with LPD **16** or other medical devices. In some examples, communication module **80** may include this wireless communication functionality.

Communication module **80** includes any suitable hardware, firmware, software or any combination thereof for communicating with another device, such as programmer **21** (FIG. **1**). Communication module **80** may transmit generated or received arrhythmia data, therapy parameter values, communications between subcutaneous ICD system **30** and LPD **16**, or any other information. For example, communication module **80** may transmit information representative of sensed physiological data such as R-R intervals or any other data that may be used by LPD **16** to determine a condition of patient **14**. Communication module **80** may also be used to receive updated therapy parameters from programmer **21**. Under the control of processor **70**, communication module **80** may receive downlink telemetry from and send uplink telemetry to programmer **21** with the aid of an antenna, which may be internal and/or external. Processor **70** may provide the data to be uplinked to programmer **21** and the control signals for the telemetry circuit within communication module **80**, e.g., via

an address/data bus. In some examples, communication module **80** may provide received data to processor **70** via a multiplexer.

Memory **72** may be configured to store a variety of operational parameters, therapy parameters, sensed and detected data, and any other information related to the monitoring, therapy and treatment of patient **14**. Memory **72** may store, for example, thresholds and parameters indicative of tachyarrhythmias and/or therapy parameter values that at least partially define delivered anti-tachyarrhythmia shocks. In some examples, memory **72** may also store communications transmitted to and/or received from LPD **16**.

Activity sensor **82** may be contained within the housing of subcutaneous ICD system **30** and include one or more accelerometers or other devices capable of detecting motion and/or position of subcutaneous ICD system **30**. For example, activity sensor **82** may include a 3-axis accelerometer that is configured to detect accelerations in any direction in space. Accelerations detected by activity sensor **82** may be used by processor **70** to identify potential noise in signals detected by sensing module **78** and/or confirm the detection of arrhythmias or other patient conditions.

In some examples, subcutaneous ICD system **30** may signal programmer **21** to further communicate with and pass the alert through a network such as the Medtronic CareLink® Network developed by Medtronic, Inc., of Minneapolis, Minn., or some other network linking patient **14** to a clinician. Subcutaneous ICD system **30** may spontaneously transmit the diagnostic information to the network or in response to an interrogation request from a user.

Power source **84** may be any type of device that is configured to hold a charge to operate the circuitry of subcutaneous ICD system **30**. Power source **84** may be provided as a rechargeable or non-rechargeable battery. In other examples, power source **84** may also incorporate an energy scavenging system that stores electrical energy from movement of subcutaneous ICD system **30** within patient **14**.

FIG. **5**A and FIG. **5**B illustrate defibrillation pulse waveforms **120**, **130**, respectively. Defibrillation pulse waveforms **120**, **130** are examples of defibrillation pulse waveforms generated by two different defibrillators. The examples may be representative of defibrillation pulses from both implantable cardiac defibrillators, e.g., ICDs, and automated external defibrillators, e.g., AEDs. Even though defibrillation pulse waveforms **120**, **130** are from different defibrillators, they both include common features that may be detected by an implantable cardiac stimulator, such as LPD **16**.

Defibrillation pulses can be monophasic or biphasic. The energy of the pulse is typically stored onto a capacitor, connected to the electrodes for a few milliseconds, and then disconnected allowing the voltage on the electrodes to return to OV. This results in a rapid leading edge, exponential decay due to the tissue load and storage capacitor, and fast falling edge. The amplitude of the second phase of the pulse is typically lower than the first since the storage capacitor has been partially discharged by the first phase of the pulse. The combination of very fast rise/fall time, such as about 1 microsecond, and large amplitude (200V-6000V) and duration (such as a few milliseconds) can be used to identify the signal as an anti-tachyarrhythmia shock.

Defibrillation pulses are typically applied from large area electrodes that are separated by a distance of several inches. The voltage level picked up by LPD electrodes, such as electrodes of LPD **16**, depends primarily on electrode separation and orientation of the LPD electrodes relative to the ICD or external defibrillator electrodes. In general, an anti-tachyarrhythmia shock seen across the LPD electrodes will vary from zero to five percent of the voltage applied across the subcutaneous ICD electrodes with a typical value of about two percent. In one example, an anti-tachyarrhythmia shock seen across the LPD electrodes equals two percent of the voltage applied across the subcutaneous ICD electrodes. Such an example may provide an amplitude of about 30 volts for a 1.5 to 2 centimeter electrode spacing on the LPD when implanted in the right ventricle apex. As mentioned above, numerous factors affect the amplitude of an anti-tachyarrhythmia shock seen across the LPD electrodes, and the amplitudes may vary accordingly. Analyzing additional pulse characteristics in addition to, or as an alternative to signal amplitude, may provide improve defibrillation pulse detection.

An anti-tachyarrhythmia shock from an ICD or AED, such as those of defibrillation pulse waveforms **120**, **130**, has extremely fast or steep edges, e.g., with rapidly changing voltage values, on the leading and trailing edges of each of the positive and negative pulse pairs. A typical mono-phasic shock will have 1 fast leading edge, and 1 fast trailing edge. A typical bi-phasic shock will have 4 fast edges (2 fast edges per pulse). As shown in FIG. **5**A, biphasic defibrillation pulse waveform **120** includes fast edges **121**, **123**, **125** and **127**. As shown in FIG. **5**B, biphasic defibrillation pulse waveform **130** includes fast edges **131**, **133**, **135**, **137** as well as a series of intermediate edges **138**, as both the positive and negative pulses are segmented.

A typical defibrillation pulse from an ICD or AED, such as those of defibrillation pulse waveforms **120**, **130**, also has an extremely large amplitude as compared to other electrical signals that may be detected by an implantable cardiac stimulator, indicated as amplitudes **122**, **126**, **132**, **136** on defibrillation pulse waveforms **120**, **130**. As discussed with respect to FIGS. **6**A and **6**B, below, the fast edges and the high amplitude typical of a defibrillation waveform may be used either separately or together to determine when an anti-tachyarrhythmia shock has occurred.

FIG. **6**A illustrates anti-tachyarrhythmia shock signal edge detector **140**, whereas FIG. **6**B illustrates an anti-tachyarrhythmia shock signal edge detector output waveform **148** during defibrillation pulse **147**. Anti-tachyarrhythmia shock signal edge detector **140** may be implemented by shock detector **99** of FIG. **3**. Anti-tachyarrhythmia shock signal edge detector **140** first receives an input of an electrical voltage across the sensing electrodes, such as electrodes **52**, **60** of LPD **16**. The sensed voltage passes through pre-filter **142** before being received by edge detector **144**. In one example, pre-filter **142** may serve as a high pass filter or differentiator to pass the fast edges through to edge detector **144**. Pre-filter **142** may also provide some low pass filtering, e.g., for frequencies greater than 10-100 kilohertz, to reduce the impact of high frequency EMI on edge detector **144** and to provide time for edge detector **144** to see the response. Pre-filter **142** may also may eliminate any DC offsets between electrodes **52** and **60** of LPD **16**. In different examples, pre-filter **142** may be a passive or active filter.

Anti-tachyarrhythmia shock signal edge detector **144** detects the edges of high amplitude pulses, as shown in FIG. **6**B. For example, edge detector **144** detects a high amplitude voltage change over a time period of not greater than 2 milliseconds, such as over a time a period of about 1 millisecond. For example, a 200-kilohertz high pass filter will lose sensitivity for changes slower than about 1.5 milliseconds, and other high pass filters will sensitivity in a similar manner according to their design and specifications.

If electrical voltage signal **141** is sensed using pacing electrodes, e.g., electrodes **52** and **60** of LPD **16**, edge detector

144 will be blanked during pacing. Blanking is used during a pace and discharge sequence to prevent a large amplitude pacing pulse from being detected as a defibrillation pulse. During pace blanking, edge detector **144** may be unable to detect an anti-tachyarrhythmia shock coincident with a pacing pulse. A single edge, as shown in FIG. **6**B is sufficient to detect an anti-tachyarrhythmia shock, for this reason, even if a portion of an anti-tachyarrhythmia shock is hidden during pace blanking, anti-tachyarrhythmia shock signal edge detector **144** may still be able to detect an anti-tachyarrhythmia shock. In the example of LPD **16**, the sensing electrodes may include tip electrode **60** and ring electrode **52** of LPD **16**. If the edges from the anti-tachyarrhythmia shock fall entirely within the pace blanking period, the anti-tachyarrhythmia shock may not be detected. However, if one of the edges falls outside the blanking period the anti-tachyarrhythmia shock will be detected. In addition, as discussed in further detail with respect to FIGS. **10-13**, a pacing pulse may include a short sensing period, in which a pacing pulse is divided into two or more windows separated by a period of no electrical stimulation, to limit the impact of blanking caused by the pacing pulse on the sensing capabilities of anti-tachyarrhythmia shock signal edge detector **140** when implemented as part of an implantable cardiac stimulator, such as LPD **16**. In such examples, the timing of the stimulation delivered by the implantable cardiac stimulator is selected such that the blanking windows caused by the delivery of the stimulation are short enough that some portion of the anti-tachyarrhythmia shock signal at the implantable cardiac stimulator electrodes will fall outside blanking and be detectable.

Anti-tachyarrhythmia shock signal edge detector **144** detects the edges of high amplitude pulses and passes that information onto digital filter **146** that determines if the edges are due to an anti-tachyarrhythmia shock. An anti-tachyarrhythmia shock that is completely hidden during pace blanking may still be detected by alternative techniques. For example, pace blanking timing is sent to digital filter **146**, which may help facilitate detection of an anti-tachyarrhythmia shock based on alternative techniques, such as defibrillation pulse polarization detector **160**, as described with respect to FIG. **8**.

FIG. **7**A illustrates signal amplitude detector **150**, whereas FIG. **7**B illustrates signal amplitude detector output waveform **158** during defibrillation pulse **157**. Signal amplitude detector **150** may be implemented by shock detector **99** of FIG. **3**. Signal amplitude detector **150** first receives an input of an electrical voltage across the sensing electrodes, such as electrodes **52**, **60** of LPD **16**. The sensed voltage passes through pre-filter **152** before being received by amplitude detector **154**. Pre-filter **152** may be configured to remove signal frequencies from the electrical voltage signal, e.g., frequencies associated with EMI, such as frequencies greater than 1-10 kilohertz. Pre-filter **152** may also eliminate any DC offsets between electrodes, such as tip electrode **60** and ring electrode **52** of LPD **16**.

Signal amplitude detector **154** is configured to detect an anti-tachyarrhythmia shock. As shown in FIG. **7**B, when signal amplitude detector **154** detects a high amplitude signal across the sensing electrodes, it outputs an indication of the high amplitude signal to digital filter **156**.

Digital filter **156** determines if the voltage amplitudes are due to an anti-tachyarrhythmia shock according to the timing of the voltage amplitudes. If electrical voltage signal **151** is being sensed using pacing electrodes, such as tip electrode **60** and ring electrode **52** of LPD **16**, amplitude detector **154** will be blanked during pacing according to the pace blanking timing signal sent to digital filter **156**. If an anti-tachyarrhythmia shock overlaps the pace pulse blanking window, digital filter **156** will attempt to piece the information together to determine if the voltage amplitude levels were due to a subcutaneous defibrillation pulse. However, if a portion of high voltage amplitude levels of a subcutaneous defibrillation pulse fall outside the blanking period, the anti-tachyarrhythmia shock will be detected. In addition, as discussed in further detail with respect to FIGS. **10-13**, a pacing pulse may include a short sensing period, in which a pacing pulse is divided into two or more windows separated by a period of no electrical stimulation, to limit the impact of blanking caused by the pacing pulse on the sensing capabilities of signal amplitude detector **150** when implemented as part of an implantable cardiac stimulator, such as LPD **16**.

FIG. **8** illustrates defibrillation pulse polarization detector **160**, which may be included as part of shock detector **99** of LPD **16**. Defibrillation pulse polarization detector may be effective at detecting defibrillation events that occur during pace blanking, even without modification of a standard pacing pulse to include a sensing period. Defibrillation pulse polarization detector **164** is configured to detect a change in the DC polarization level at the sensing electrodes, such as electrodes **52**, **60** of LPD **16**, due to a defibrillation pulse as reflected in electrode voltage signal **161**.

Defibrillation pulse polarization detector **160** first receives an input of an electrical voltage across the sensing electrodes, such as electrodes **52**, **60** of LPD **16**. The sensed voltage passes through pre-filter **162** before being received by polarization detector **164**. Pre-filter **162** may serve as a high pass filter and/or differentiator. If a large voltage is applied across sensing electrodes, such the tip and ring electrodes of LPD **16**, the voltage will be clamped by the input protection network of LPD **16** or other implantable pacing device, resulting in a large current flow. This large current may result in a large polarization voltage between the sensing electrodes. As an example, if the open circuit between sensing electrodes is 50 volts as a result of an anti-tachyarrhythmia shock, Zener protection diodes of the device clamp at 10 volts, and the impedance between the electrodes is 500 ohms, there will be a current of 40 volts/500 ohms equals 80 milliamps. A current of 80 milliamps applied for 5 milliseconds duration of an anti-tachyarrhythmia shock results in a total charge of 400 microcoulombs into the sensing electrodes, resulting in electrode voltage **161**. If the sensing electrodes capacitance is 400 microfarad, a polarization voltage of about 1 volt will result. This large "DC" polarization voltage will typically remain for a long time, likely much longer than 10 milliseconds, and perhaps seconds following an anti-tachyarrhythmia shock, thereby creating signature of an anti-tachyarrhythmia shock detectable well after the anti-tachyarrhythmia shock. While the electrical configuration of sensing electrodes within an LPD is much more complex than a simple resistor and capacitor, the basic concepts of capacitance and resistance still apply. The particular design of a cardiac stimulator, such as LPD **16**, may be tested in a controlled setting to determine the signature polarization voltage of an anti-tachyarrhythmia shock for that particular design of a cardiac stimulator.

Polarization detector **160** may be especially useful at detecting defibrillation pulses that occur during pace blanking. In defibrillation pulse amplitude detector **150** and anti-tachyarrhythmia shock signal edge detector **140**, an anti-tachyarrhythmia shock that occurs entirely within pace blanking may be undetected. In contrast, polarization detector **160** may detect a significant change in voltage, e.g., greater than a threshold across sensing electrodes, from before a pace blanking period to after the pace blanking period as an indication of a defibrillation pulse. Typically,

after a pace there will be a relatively smaller polarization which decays away over several milliseconds following the pace and discharge sequence. In contrast, polarization resulting from an anti-tachyarrhythmia shock will be much larger and/or longer lasting than polarization resulting from a pace.

Digital filter **166** may be used to analyze the change in voltage from before a pace blanking period to after the pace blanking period to detect the presence of an anti-tachyarrhythmia shock. In addition, as discussed in further detail with respect to FIGS. **10-13**, a pacing pulse may include a short sensing period, in which a pacing pulse is divided into two or more windows separated by a period of no electrical stimulation, to improve the sensing capabilities of polarization detector **160** when implemented as part of an implantable cardiac stimulator, such as LPD **16**, by limiting the duration of any pace blanking period, thereby further increasing the sensitivity of polarization detector **160**.

The detection techniques discussed with respect to FIGS. **6A-8** may be combined in any manner, e.g., any one or more of the detection techniques may be implemented in shock detector **99** of LPD **16**. In addition, implementation of the detection techniques discussed with respect to FIGS. **6A-8** may vary from the examples described above. In some examples, multiple detectors may be used to increase sensitivity. In some particular examples, an amplitude detector may be combined with either an edge detector to improve sensitivity just prior to and after blanking or alternatively with a polarization detector to improve sensitivity for shocks occurring during blanking. In addition, a detector, such as any of detectors **140**, **150**, **160**, may be blanked during pacing pulses, either electrically or through digital filtering, to prevent detecting pacing pulses as defibrillation pulses.

Digital filtering, such as that provided by filters **146**, **156**, **166**, may be used to discriminate between electro-surgery, RF ablation, and other electrical signals as compared to an anti-tachyarrhythmia shock. In this manner, such digital filtering provide an additional level of discrimination to prevent high current events such as electro-surgery, RF ablation, EMI, or continuous wave induction from being detected as a HV therapy. Defibrillation waveforms typically have durations of approximately 5 milliseconds per phase, but this may vary depending on the load impedance and manufacturer from a minimum of about 1-2 milliseconds to a maximum of about 15-30 milliseconds per phase. Electro-surgery and RF ablation equipment typically use high frequencies much higher than a defibrillation pulse (100 kilohertz to 1 megahertz). In one example, digital filtering may detect these very high frequencies and block a digital shock detect signal from being generated when the comparators are toggling at frequencies greater than approximately 100 kilohertz.

When an ICD is implanted may be tested to insure it is capable of defibrillating the patient. Testing the ICD may include inducing ventricular fibrillation. Induction waveforms typically use a continuous wave AC current of 0.2 amps with a frequency of approximately 50 hertz and a total duration between 1 and 10 seconds. Digital filtering may detect the induction by detecting that the comparators are toggling at a rate greater than 25 hertz for a time period longer than expected for a defibrillation pulse, such as 100 milliseconds. When a long burst of AC current is detected, a digital filter may generate a signal indicating that a continuous AC signal has been detected and either block the digital shock detect signal from being generated or generate a signal which can be used by the CPU to prevent acting on the falsely detected shock. Detecting continuous wave EMI may also be useful to prevent false detections of shocks in the presence of extreme EMI sources such as welding equipment or high voltage power lines. A digital filter may also include the capability to allow only one shock detection pulse to be generated from each defibrillation pulse regardless of the number of edges or phases detected by preventing pulses from being generated at a rate no faster than approximately once every 100 milliseconds. A digital filter may do this by requiring a time interval of approximately 100 milliseconds without any detections from the comparator before allowing another shock detect to be generated by the digital filter.

In examples in which a shock detector implements two or more of detectors **140**, **150**, **160**, the detectors may implement common functionality as common hardware and/or software. For example, the same hardware used to detect the large amplitude associated with an anti-tachyarrhythmia shock may detect the level change associated with a polarization shift during blanking. As another example, the same hardware used to detect the large amplitude could be used for edge detection if the bandpass filter is shifted. In addition, within an implantable cardiac stimulator, such as LPD **16**, a sense amplifier used to detect cardiac signals, including, but not limited to, R-waves and P-waves may also be used to detect defibrillation pulses, although the range of the detected electrical signals associated with defibrillation pulses will generally be different from the ranges of cardiac signals. For example, sensing electrical signals associated with defibrillation pulses may result in sensing electrical signals of a magnitude exceeding about 50 millivolts, whereas sensing cardiac signals may result in sensing electrical signals of a magnitude less than about 50 millivolts.

In one particular example, a typical comparator may have a threshold exceeding about 50 millivolts, such as set to 100 millivolts. In the example of a threshold set to 100 millivolts, an input signal of about 200 millivolts-peak would result in a filtered signal exceeding the 100 millivolts threshold. In some examples, a comparator threshold may be adjustable, such as adjustable with a range of about 50 millivolts to about 200 millivolts, which may be suitable for a device with an electrode spacing, such as tip to ring electrode spacing of about 1.8 centimeters. However, suitable threshold settings or ranges may vary for different electrode configurations and/or spacings. For example, devices with larger or smaller tip to ring spacing may need higher or lower threshold voltage. Generally, the threshold should be set above the maximum expected input level for EMI, intrinsic events, and pacing polarization with sufficient margin to generally avoid detection of a combinations of all of these events while still allowing capture of defibrillation events.

In the particular example of the same hardware being used to detect an amplitude and edge detection (as with detectors **140** and **150**), the bandpass filter provided by pre-filter modules **142**, **152**, **162** may be modified. Such an implementation may include a 1 nanofarad EMI filter capacitor adjacent to the electrodes with an input clamped by Zener-triggered triac of plus or minus 2 volts, a 1 megaohm limit resistor, the resistor may be shared with a cardiac signal sense amplifier, ESD input protect diodes of plus or minus 1 volts, also shared with the cardiac signal sense amplifier. A bandpass filter may include a 5 kilohertz low pass filter shared with the cardiac signal sense amplifier, a 200 hertz high pass filter to suppress DC offset and polarization and a 1 kilohertz low pass filter to suppress EMI. Such defibrillation detection hardware may further include an adjustable threshold of plus or minus 50-300 millivolts, two clocked comparators to detect threshold crossing and further include digital filtering for excessive EMI. These specific references to hardware for detection

defibrillation pulses are merely examples and any number of modifications may be made to the digital and analog hardware implementations described.

As discussed previously, detection of an anti-tachyarrhythmia shock may be used to adjust the functionality of a cardiac stimulator, such as LPD **16**. For example, following the detection of an anti-tachyarrhythmia shock, the cardiac stimulator may perform one or more actions, including, but not limited to: aborting ATP, initiating post-shock pacing, increasing pacing amplitude and pulse width after the shock to increase likelihood of capture if the anti-tachyarrhythmia shock causes temporary rise in capture threshold due to stunning or polarization on lead interface, resetting the V-V timing so the first pace after a shock occurs at correct V-V time delay, clearing off the pacing AC coupling capacitor so any charge built up on the capacitor or at the lead interface will not impact delivered pacing amplitude, recharging the pacing capacitor to the correct voltage in case the anti-tachyarrhythmia shock affects the voltage by causing switches to turn on, temporarily switching in a lower value resistor, such as a 20 kilo-ohm rather than 5 mega-ohm resistor, to bleed the polarization/charge off the lead interface and/or AC coupling capacitor after a shock, and increasing discharge time and/or blanking times for the sense amplifier to reduce likelihood of over sensing the lead polarization after a pace. In addition, the cardiac stimulator may flag the event of the detection of the anti-tachyarrhythmia shock and store for diagnostic information.

Experimental Results (FIGS. **9**A-**9**C)

FIGS. **9**A-**9**C illustrate examples of defibrillation pulse polarization resulting from an anti-tachyarrhythmia shock occurring on or shortly after a pacing pulse. FIGS. **9**A-**9**C demonstrate the ability to detect an anti-tachyarrhythmia shock using defibrillation pulse polarization techniques as described with respect to defibrillation pulse polarization detector **160**. During the testing represented by FIGS. **9**A-**9**C, pacing electrodes of a cardiac stimulation device configured to perform sensing as discussed with respect to FIGS. **6**A-**8** were located in a saline solution with defibrillation electrodes of a separate defibrillation device. For example, the pacing electrodes may represent electrodes of LPD **16**. As indicated by FIGS. **9**A-**9**C, defibrillation pulse polarization resulted in a voltage change on sensing/pacing electrodes of at least about 1 volt.

FIG. **9**A illustrates electrode voltage **172**, which represents voltage across electrodes of an LPD, such as electrodes **52**, **60** of LPD **16**, and tank voltage **174**, which represents the voltage across the defibrillation electrodes in the experimental tank. Tank voltage **174** is used to simulate an anti-tachyarrhythmia shock. FIG. **9**A further illustrates tip current **176**, which represents the current through the electrodes of the LPD, again simulating an anti-tachyarrhythmia shock.

Electrode voltage **172** includes spikes due to a biphasic defibrillation pulse as represented by tip current **176**. Electrode voltage **172** not only represents the response to tip current **176**, but also includes a pace blanking period **173**. The pace blanking period **173** is coincident with a pacing pulse delivered by the LPD during a positive phase of the anti-tachyarrhythmia shock, a time with voltage amplitude or fast edge sensing may be blanked. Tank voltage **174** represents the total voltage differential across a tank holding the saline solution. The pacing pulse of FIG. **9**A occurred during the second phase of the biphasic defibrillation pulse, but the spikes in electrode voltage **172** are still apparent.

FIG. **9**B illustrates electrode voltage **182**, which represents voltage across electrodes of an LPD, such as electrodes **52**, **60** of LPD **16**, and tank voltage **184**, which represents the voltage across the electrodes in the experimental tank. Tank voltage **184** is used to simulate an anti-tachyarrhythmia shock. FIG. **9**B further illustrates tip current **186**, which represents the current through the electrodes of the LPD, again simulating an anti-tachyarrhythmia shock. The pacing pulse of FIG. **9**B occurs prior to the biphasic defibrillation pulse, and the spikes in electrode voltage **182** are detectable.

Similarly, FIG. **9**C illustrates electrode voltage **192**, which represents voltage across electrodes of an LPD, such as electrodes **52**, **60** of LPD **16**, and tank voltage **194**, which represents the voltage across the electrodes in the experimental tank. Tank voltage **194** is used to simulate an anti-tachyarrhythmia shock. FIG. **9**C further illustrates tip current **186**, which represents the current through the electrodes of the LPD, again simulating an anti-tachyarrhythmia shock. The pacing pulse of FIG. **9**C occurring prior to the biphasic defibrillation pulse, and the spikes in electrode voltage **192** are detectable.

FIG. **10** illustrates an example waveform **200** of biphasic cardiac pacing, such as ATP pacing, including a pacing pulse having two windows, an initial negative discharge pacing window **202**, and a subsequent positive discharge window **206**, separated by a period of substantially no stimulation **204**, the period of no stimulation **204** being suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock. In one example, the period of no stimulation **204** may have a duration between about 1 millisecond to about 20 milliseconds. In another example, the period of no stimulation **204** may have a duration about 5 milliseconds to about 10 milliseconds. In one particular example, the period of no stimulation **204** may be about 10 milliseconds. The period of no stimulation **204** may be used to detect an anti-tachyarrhythmia shock with anti-tachyarrhythmia shock signal edge detector **140** and/or defibrillation pulse amplitude detector **150**. Specifically, the period of no stimulation **204** allow for sensing with anti-tachyarrhythmia shock signal edge detector **140** and/or defibrillation pulse amplitude detector **150**. This reduces the probability that an anti-tachyarrhythmia shock would fail to be detected due to blanking because one of the detectable artifacts of the resulting electrical signal should fall within the period of no stimulation **204** (where monitoring is resumed) and be detected.

FIG. **11** illustrates an example waveform **210** of biphasic cardiac pacing, such as ATP pacing, including a pacing pulse having three pacing windows and two periods of substantially no stimulation. More specifically, waveform **210** includes an initial negative discharge pacing window **212**, a relatively short period of substantially no stimulation **214**, and a subsequent positive discharge window **216**, then a relatively long period of substantially no stimulation **215**, followed by a second positive discharge window **217**. The periods of no stimulation **214**, **215** are suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock. In one example, the period of no stimulation **214** may have a duration between about 0.2 milliseconds to about 5 milliseconds. In another example, the period of no stimulation **215** may have a duration about 1 milliseconds to about 20 milliseconds. In one particular example, the period of no stimulation **214** may be about 1 millisecond and the period of no stimulation **215** may be between about 3 millisecond to about 20 milliseconds. A period of no stimulation **214**, **215** may be used to detect an anti-tachyarrhythmia shock with anti-tachyarrhythmia shock signal edge detector **140** and/or defibrillation pulse amplitude detector **150**. Specifically, each period of no stimulation **214**, **215** allows for sensing with anti-tachyarrhythmia shock sig-

nal edge detector **140** and/or defibrillation pulse amplitude detector **150**. This reduces the probability that an anti-tachyarrhythmia shock would fail to be detected due to blanking because at least one of the detectable artifacts of the resulting electrical signal should fall within one of the periods of no stimulation (where monitoring is resumed) and be detected.

FIG. **12** illustrates an example waveform **220** of biphasic cardiac pacing, such as ATP pacing, including a pacing pulse having multiple windows, an initial negative discharge pacing window **222** and a series of positive discharge windows **226**, each of less than about 5 milliseconds or even about 2 milliseconds. Adjacent positive discharge windows **226** are separated by periods of substantially no stimulation **224**. The periods of no stimulation **224** are suitable for sensing electrical signals, including electrical signals indicative of an anti-tachyarrhythmia shock. In one example, each period of no stimulation **224** may have a duration between about 0.1 millisecond to about 20 milliseconds. In another example, a period of no stimulation **224** may have a duration about 5 milliseconds to about 10 milliseconds. In one particular example, a period of no stimulation **224** may be about 1 milliseconds. A period of no stimulation **224** may be used to detect an anti-tachyarrhythmia shock with anti-tachyarrhythmia shock signal edge detector **140** and/or defibrillation pulse amplitude detector **150**. Waveform **220** allows for a short pace blanking time relative of the duration of an anti-tachyarrhythmia shock such that would be impossible to hide it completely within the blanking period. This reduces the probability that an anti-tachyarrhythmia shock would fail to be detected due to blanking because at least one of the detectable artifacts of the resulting electrical signal should fall within one of the periods of no stimulation (where monitoring is resumed) and be detected. However, pacing according to waveform **220** may leave more polarization behind following discharge pacing window **222** since the charge from the pace will not be immediately compensated for by charge from the discharge. A higher threshold for defibrillation pulse amplitude detector **150** may be required to prevent detection of the pacing pulse polarization. For example, the threshold could be boosted higher immediately after a pace pulse (twice as large for example) and then decreased gradually during the series of positive discharge windows **226** or all at once at the end of the discharge sequence.

FIG. **13** illustrates an example waveform **230** of monophasic cardiac pacing, such as ATP pacing, including a pacing pulse having two windows, an initial discharge negative pacing window **232**, and a subsequent negative pacing window **236**, separated by a period of substantially no stimulation **234**, the period of no stimulation **234** being suitable for sensing electrical signals, such including electrical signals indicative of an anti-tachyarrhythmia shock. In one example, the period of no stimulation **234** may have a duration between about 0.2 milliseconds to about 20 milliseconds. In another example, the period of no stimulation **234** may have a duration between about 5 milliseconds to about 10 milliseconds. In one particular example, the period of no stimulation **234** may be about 1 millisecond. The period of no stimulation **234** may be used to detect an anti-tachyarrhythmia shock with anti-tachyarrhythmia shock signal edge detector **140** and/or defibrillation pulse amplitude detector **150**. This reduces the probability that an anti-tachyarrhythmia shock would fail to be detected due to blanking because at least one of the detectable artifacts of the resulting electrical signal should fall within the period of no stimulation (where monitoring is resumed) and be detected.

FIG. **14** is a flow diagram of an example process for delivering tachyarrhythmia therapy by LPD **16**, which includes detecting an anti-tachyarrhythmia shock delivered by another device. The example of FIG. **14** will be described with respect to LPD **16** operating without direct communication to subcutaneous ICD system **30**. In this manner, LPD **16** is capable of determining when to terminate ATP and/or initiate post-shock pacing without any instruction from another device, such as subcutaneous ICD system **30** or other internal or external defibrillation device.

As shown in FIG. **14**, processor **90** of LPD **16** may monitor a cardiac rhythm from an electrical signal sensed from heart **18** (**280**). This monitoring may occur during a period of time when shock detector **99** is off or disabled. Disabling of shock detector **99** may reduce power consumption by LPD **16** and extend the battery life of power source **102**. Therefore, processor **90** may need to enable shock detector **99** at some point during operation of LPD **16**. In alternative examples, shock detector **99** may be operated continuously or periodically in a functionally continuous manner. In other alternative examples, the sense amplifier may provide an indication of a shock when the normal shock detector is disabled, and the shock detector would provide detection of a shock when it is enabled.

If processor **90** detects that the shock detector should be enabled (e.g., detect an arrhythmia eligible for anti-tachyarrhythmia shock therapy) ("YES" branch of block **282**), processor **90** proceeds to enable shock detector **99**. If processor **90** determines that the shock detector does not need to be enabled ("NO" branch of block **282**), processor **90** may continue to monitor heart **18** for tachyarrhythmias (**280**).

If processor **90** determines that the shock detector does need to be enabled ("YES" branch of block **282**), processor **90** may enable the shock detector **99** (**288**). Shock detector **99** detects the anti-tachyarrhythmia shock by measuring the voltage across the electrode inputs of the implanted device according to one or more of techniques for detection of an anti-tachyarrhythmia shock by an LPD or other device: detection of the high level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, and detection of a large post-shock polarization change. Each technique looks for a different electrical signal characteristic. Shock detector **99** may combine one or more of these techniques to improve sensitivity and/or specificity. For example, the high level of an anti-tachyarrhythmia shock may be combined with one or both of the detection of a high slew rate of the leading and trailing edges, and the detection of a large post-shock polarization change.

If shock detector **99** detects a delivered shock ("YES" branch of block **288**), processor **90** may begin post-shock pacing to heart **18** of patient **14** (**292**). Alternatively, or additionally, processor **90** may terminate ATP therapy. Processor **90** may start post-shock pacing by causing LPD **16** to enter a post-shock pacing mode. Detection of the anti-tachyarrhythmia shock may be used to abort and/or temporarily suspend the delivery of ATP and to activate post-shock pacing, such as VVI post-shock pacing. ATP may be temporarily suspended following an anti-tachyarrhythmia shock to insure that the pacing pulses will not induce another arrhythmia. Post-shock pacing may be used to insure pacing support if the patient's heart does not begin to beat normally immediately following an anti-tachyarrhythmia shock. A higher than normal amplitude and pulse width is commonly used to minimize the risk of loss of capture following an anti-tachyarrhythmia shock. A higher capture threshold may occur as a result of tissue stunning due to elevated current in the myocardial tissue from the anti-tachyarrhythmia shock delivery. A higher threshold may also occur as a result of physiological changes in the tissue resulting from lack of blood flow to the myocardium during

VF. Furthermore, after an anti-tachyarrhythmia shock there can be increased polarization at the lead interface resulting in the need for a higher voltage to overcome the lead polarization.

If no shock has been detected ("NO" branch of block **288**), processor **90** may check to if the enabled shock detector period has timed out. Processor **90** may track a period of time since shock detector **99** was enabled, and if the period of time exceeds a timeout threshold, processor **90** may disable shock detector **99** and continue to monitor ECGs for tachyarrhythmias (**280**). If the period after enabling shock detector **99** has not exceeded the timeout threshold ("NO" branch of block **290**), processor **90** may continue to determine if any shocks have been detected (**288**).

In some examples, prior to delivering post-shock pacing, processor **90** may analyze sensed electrical signals from heart **18** to determine whether or not post-shock pacing is necessary. Processor **90** may analyze an ECG or other electrical signal to detect bradycardia and/or asystole. In response to the detection of bradycardia or asystole, processor **90** may begin post-shock pacing. Processor **90** may, in some example, determine one or more post-shock pacing parameters based on which rhythm was detected and/or characteristics of the detected rhythm. In response to not detecting bradycardia or asystole, processor **90** may withhold post-shock pacing and again look for any delivered shock (**288**).

After starting post-shock pacing (**292**), processor **90** may continue to determine if shock detector **99** detects any additional shocks from subcutaneous ICD system **30** or another device (**294**). If processor **90** detects another shock ("YES" branch of block **294**), processor **90** may restart the post-shock pacing (**292**). Processor **90** may also track a period of time following the delivery, or the starting of delivery, of post-shock pacing (**296**). If processor **90** determines that the period of time following initial delivery of post-shock pacing does not exceed a timeout threshold ("NO" branch of block **296**), processor **90** will continue to determine if another shock has been detected (**294**). If, however, processor **90** determines that the period of time following starting of post-shock pacing exceeds the timeout threshold ("YES" branch of block **296**), processor **90** may responsively terminate post-shock pacing (**298**). Processor **90** may then return to determine if another shock has been detected (**288**) or if the shock detector should be disabled (**280**). In other examples, processor **90** may continue post-shock pacing for an undetermined period of time following detection of the shock. In some examples, LPD **16** may even continue post-shock pacing during subsequent shocks.

FIG. **15**A illustrates an example circuit **300** that provides analog shock signal detection suitable for inclusion as part of sensing module **98** and shock detector **99**. Circuit **300** receives a voltage from LPD electrodes **302**, **304**. Electrode **304** is connected to ground. In one example, electrode **304** may represent a housing electrode of the IMD. Circuit **300** includes bandpass filter **306**, which may be a 200 hertz to 1 kilohertz bandpass filter. Bandpass filter **306** functions to limit signal noise that may otherwise be detected as an anti-tachyarrhythmia shock, and the range of bandpass filter **306** may be selected accordingly.

Bandpass filter **306** outputs filtered signal **308** to comparators **310**, **312**. Comparator **310** indicates to digital filter **314** when a positive voltage has an amplitude that exceeds a predefined level Vthp, whereas comparator **312** indicates to digital filter **314** when a negative voltage has an amplitude that exceeds a predefined level Vthm. Thus, comparators **310**, **312** combine detect when the magnitude of the filtered signal from bandpass filter **306** exceeds programmed threshold voltages of comparators **310**, **312**. Digital filter **314** receives the signals from comparators **310**, **312** and outputs a digital detection signal **316** according to one or more shock detection techniques as described herein including a relatively high amplitude level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, detection of a large post-shock polarization change, or any combination thereof.

In some examples, a different bandpass filter may be used in combination with bandpass filter **306** to facilitate detection of cardiac signals using digital filter **314**. For example, a cardiac signal detection bandpass filter may have a range of about 20 hertz to about 70 hertz. This may allow circuit **300** to be implemented in combination with cardiac signal detection circuitry within an cardiac stimulator such as an LPD as such an implementation would only require the addition of bandpass filter **306** and comparators **310**, **312** to cardiac signal detection circuitry.

FIG. **15**B illustrates an example circuit **320** that provides digital shock signal detection suitable for inclusion as part of sensing module **98** and shock detector **99**. Circuit **320** receives a voltage from LPD electrodes **322**, **324**. Electrode **324** is connected to ground. In one example, electrode **324** may represent a housing electrode of the IMD. Circuit **320** includes bandpass filter **326**, which may be a 200 hertz to 1 kilohertz bandpass filter. Bandpass filter **326** functions to limit signal noise that may otherwise be detected as an anti-tachyarrhythmia shock, and the range of bandpass filter **326** may be selected accordingly.

Circuit **320** further includes analog to digital converter **330** to digitize the filtered input **328**. Digital filter and detector **334** receives the digital signal from analog to digital converter **330** and outputs a digital detection signal **336** according to one or more anti-tachyarrhythmia shock detection techniques as described herein including a relatively high amplitude level of an anti-tachyarrhythmia shock, detection of a high slew rate of the leading and trailing edges, detection of a large post-shock polarization change, or any combination thereof.

In some examples, a different bandpass filter may be used in combination with bandpass filter **326** to facilitate detection of cardiac signals using digital filter **334**. For example, a cardiac signal detection bandpass filter may have a range of about 20 hertz to about 70 hertz. This may allow circuit **320** to be implemented in combination with cardiac signal detection circuitry within an cardiac stimulator such as an LPD as such an implementation would only require the addition of bandpass filter **326** to cardiac signal detection circuitry.

Alternatively, the different filtering ranges for detection of cardiac signals as compared to detection of anti-tachyarrhythmia shock may be implemented digitally, e.g., by digital filter and detector **334**. In such an example, bandpass filter **326** may provide a comparatively large range or distinct ranges to allow cardiac signals, e.g., 20 hertz to about 70 hertz, as well as anti-tachyarrhythmia shock signals, e.g., 200 hertz to 1 kilohertz, to be included in filtered signal **328** received by analog to digital converter **330**.

The disclosure contemplates computer-readable storage media comprising instructions to cause a processor to perform any of the functions and techniques described herein. The computer-readable storage media may take the example form of any volatile, non-volatile, magnetic, optical, or electrical media, such as a RAM, ROM, NVRAM, EEPROM, or flash memory. The computer-readable storage media may be referred to as non-transitory. A programmer, such as patient programmer or clinician programmer, or other computing device may also contain a more portable removable memory type to enable easy data transfer or offline data analysis.

The techniques described in this disclosure, including those attributed to subcutaneous ICD system **30**, LPD **16**, programmer **21**, and various constituent components, may be implemented, at least in part, in hardware, software, firmware or any combination thereof. For example, various aspects of the techniques may be implemented within one or more processors, including one or more microprocessors, DSPs, ASICs, FPGAs, or any other equivalent integrated or discrete logic circuitry, as well as any combinations of such components, embodied in programmers, such as physician or patient programmers, stimulators, remote servers, or other devices. The term "processor" or "processing circuitry" may generally refer to any of the foregoing logic circuitry, alone or in combination with other logic circuitry, or any other equivalent circuitry.

Such hardware, software, firmware may be implemented within the same device or within separate devices to support the various operations and functions described in this disclosure. For example, any of the techniques or processes described herein may be performed within one device or at least partially distributed amongst two or more devices, such as between subcutaneous ICD system **30**, LPD **16** and/or programmer **21**. In addition, any of the described units, modules or components may be implemented together or separately as discrete but interoperable logic devices. Depiction of different features as modules or units is intended to highlight different functional aspects and does not necessarily imply that such modules or units must be realized by separate hardware or software components. Rather, functionality associated with one or more modules or units may be performed by separate hardware or software components, or integrated within common or separate hardware or software components.

The techniques described in this disclosure may also be embodied or encoded in an article of manufacture including a non-transitory computer-readable storage medium encoded with instructions. Instructions embedded or encoded in an article of manufacture including a non-transitory computer-readable storage medium encoded, may cause one or more programmable processors, or other processors, to implement one or more of the techniques described herein, such as when instructions included or encoded in the non-transitory computer-readable storage medium are executed by the one or more processors. Example non-transitory computer-readable storage media may include random access memory (RAM), read only memory (ROM), programmable read only memory (PROM), erasable programmable read only memory (EPROM), electronically erasable programmable read only memory (EEPROM), flash memory, a hard disk, a compact disc ROM (CD-ROM), a floppy disk, a cassette, magnetic media, optical media, or any other computer readable storage devices or tangible computer readable media.

In some examples, a computer-readable storage medium comprises non-transitory medium. The term "non-transitory" may indicate that the storage medium is not embodied in a carrier wave or a propagated signal. In certain examples, a non-transitory storage medium may store data that can, over time, change (e.g., in RAM or cache).

Various examples have been described for delivering cardiac stimulation and defibrillation therapies as well as coordinating the operation of separate LPDs and subcutaneous ICDs implanted within a patient. Any combination of the described operations or functions is contemplated. These and other examples are within the scope of the following claims.

What is claimed is:

1. A method for detecting, with an implantable pacemaker, delivery of an anti-tachyarrhythmia shock by another device comprising:

delivering, by the implantable pacemaker, cardiac stimulation therapy;

sensing, by the implantable pacemaker via an electrode pair within the patient, an electrical signal;

detecting, by the implantable pacemaker, the anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the electrode pair within the patient; and

altering the cardiac stimulation therapy delivered by the implantable pacemaker based on the detected anti-tachyarrhythmia shock.

2. The method of claim **1**, wherein detecting the anti-tachyarrhythmia shock based on the sensed electrical signal further includes detecting an edge of the anti-tachyarrhythmia shock based on a change in voltage at or greater than a predetermined edge detection voltage amplitude threshold and over a time period of not greater than about 2 milliseconds within the sensed electrical signal.

3. The method of claim **2**, wherein detecting the anti-tachyarrhythmia shock based on the sensed electrical signal further includes detecting a voltage at or greater than a predetermined amplitude threshold within the sensed electrical signal.

4. The method of claim **1**, wherein detecting the anti-tachyarrhythmia shock based on the sensed electrical signal further includes detection of a change in voltage at or greater than a predetermined amplitude threshold within the sensed electrical signal.

5. The method of claim **1**, further comprising delivering anti-tachycardia pacing to the heart of the patient prior to detecting the anti-tachyarrhythmia shock.

6. The method of claim **5**, further comprising:

upon detecting the anti-tachyarrhythmia shock based on the sensed electrical signal, refraining from the delivery of anti-tachycardia pacing to the heart of the patient; and

upon detecting the anti-tachyarrhythmia shock based on the sensed electrical signal, delivering post-shock pacing therapy.

7. The method of claim **5**,

wherein the cardiac stimulation therapy includes a pacing pulse with two windows separated by a period of substantially no stimulation, the period of substantially no stimulation being between about 20 milliseconds to about 1 millisecond, and

wherein sensing, from the electrode pair within the patient, includes sensing during the period of substantially no stimulation of the pacing pulse.

8. The method of claim **1**, wherein the anti-tachyarrhythmia shock was delivered by one of:

an implantable medical device; and

an external medical device.

9. The method of claim **1**, wherein the anti-tachyarrhythmia shock is one of:

a defibrillation pulse; and

a cardioversion pulse.

10. The method of claim **1**, wherein delivering, by the implantable pacemaker, cardiac stimulation therapy, includes delivering the cardiac stimulation therapy via the electrode pair.

11. An implantable pacing device comprising:

an electrode pair;

a signal generator configured to deliver cardiac stimulation therapy to a heart of a patient;

a shock detector configured to sense, from the electrode pair when the implantable medical device is implanted within a patient, an electrical signal; and

a processor configured to detect an anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the electrode pair within the patient, and alter the cardiac stimulation therapy based on the detected anti-tachyarrhythmia shock.

12. The implantable pacing device of claim **11**, wherein the processor is configured to detect the anti-tachyarrhythmia shock further based on a change in voltage at or greater than a predetermined edge detection voltage amplitude threshold and over a time period of not greater than about 2 milliseconds within the sensed electrical signal.

13. The implantable pacing device of claim **11**, wherein the processor is configured to detect the anti-tachyarrhythmia shock further based a change in voltage at or greater than a predetermined amplitude threshold within the sensed electrical signal.

14. The implantable pacing device of claim **11**, wherein altering the cardiac stimulation therapy based on the detected anti-tachyarrhythmia shock comprises:

upon detecting the anti-tachyarrhythmia shock based on the sensed electrical signal, refraining from the delivery of anti-tachycardia pacing; and

upon detecting the anti-tachyarrhythmia shock based on the sensed electrical signal, delivering post-shock pacing therapy via the signal generator.

15. The implantable pacing device of claim **11**, wherein the implantable pacing device is a leadless pacing device, the leadless pacing device further comprising:

a housing configured to be implanted within the heart of the patient, the electrode pair being coupled to the housing; and

a fixation mechanism configured to attach the housing to tissue of the heart.

16. The implantable pacing device of claim **11**,

wherein the cardiac stimulation therapy includes a pacing pulse with two or more windows separated by one or more period of substantially no stimulation, the periods of substantially no stimulation being between about 0.1 milliseconds to about 20 milliseconds,

wherein the shock detector configured to sense, from the electrode pair within the patient, the electrical signal during the periods of substantially no stimulation of the pacing pulse.

17. The implantable pacing device of claim **11**, wherein the signal generator is configured to deliver the cardiac stimulation therapy to the heart of the patient via the electrode pair.

18. A system comprising:

a subcutaneous implantable cardioverter defibrillator comprising a first set of electrodes and configured to:

sense a first electrical signal from a heart of a patient via the one or more first electrodes;

detect a tachyarrhythmia within the sensed first electrical signal; and

determine, based on the detected tachyarrhythmia, to deliver anti-tachyarrhythmia shock therapy to the patient to treat the detected arrhythmia; and

a leadless pacing device configured to be implanted within the heart of the patient, wherein the leadless pacing device comprises:

a second set of electrodes;

a signal generator configured to deliver stimulation therapy to the heart of the patient;

a shock detector configured to sense, from the second set of electrodes when the leadless pacing device is implanted within a patient, an electrical signal; and

a processor configured to detect an anti-tachyarrhythmia shock based on the sensed electrical signal by detecting DC voltage polarization across the second set of electrodes within the patient, and alter the cardiac stimulation therapy based on the detected anti-tachyarrhythmia shock.

19. The system of claim **18**, wherein the processor is configured to detect the anti-tachyarrhythmia shock further based a change in voltage at or greater than a predetermined amplitude threshold within the sensed electrical signal.

20. The system of claim **18**,

wherein the stimulation therapy includes a cardiac pacing pulse with two or more windows separated by one or more period of substantially no stimulation, the periods of substantially no stimulation being between about 0.1 milliseconds to about 20 milliseconds,

wherein the shock detector configured to sense, from the electrode pair within the patient, the electrical signal during the periods of substantially no stimulation of the pacing pulse.

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